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AN ANALYTICAL MODEL FOR PREDICTING THE RADIATION FROM JET PLUMES IN THE MID-INFRARED SPECTRAL REGION

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AN ANALYTICAL MODEL FOR PREDICTING THE RADIATION FROM JET PLUMES IN THE MID-INFRARED SPECTRAL REGION

by

H. Tracy Jackson

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ABSTRACT

This report describes an analytical model for predicting the emission of radiation from a jet plume in the mid-infrared spectral region. It is assumed that the dominant radiation arises for the CO_2 molecule. Results are therefore reported for the 4.3-micrometer band of gaseous carbon dioxide which is assumed to cover the spectral region 2050 to 2400 cm^{-1} (4.17 - 4.88 micrometers). The temperature range that is considered varies from 300° to 2100°K. The objective of the reported program was to develop a computerized program for predicting radiant energy emissions which could be readily integrated into a flow field calculation. A description is given of both the radiation model and the flow field model. The described program provides both the spectral and spatial intensity distributions of the emitted radiation.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Concluded)

Section I. INTRODUCTION

This report presents the results of the second phase of a program* which has been undertaken to predict analytically the spectral and spatial distribution of radiation emitted from an inhomogeneous, nonisothermal system of hot gases. Results are reported for the 4.3-micrometer band of gaseous carbon dioxide (CO_2) which is assumed to cover the spectral region 2050 to 2400 cm^{-1} (4.17 to 4.88 micrometers). The temperature range that is considered varies from 300° to 2100°K. It was pointed out in the first phase [1] of this study that the program was initiated because of current interest in being able to predict the radiant energy emitted by a particular system of hot gases in narrow bands of the infrared spectrum. The objective of the program was to develop a computerized computational scheme for predicting radiant energy emissions which could be readily integrated into a flow field calculation. Such a program readily provides both the spectral and spatial intensity distribution of the emitted radiation.

In particular, this report outlines the current status of the program with emphasis on modeling the radiation emitted from the hot gaseous combustion products of fixed wing jet aircraft in the mid-infrared portion of the spectrum. It is well established that one of the major sources of radiation emitted from a jet aircraft is the radiation emitted from the hot jet plume. This is particularly true when the aircraft is viewed from a direction such that the hot tail pipe is not seen. Since jet fuels are largely hydrocarbons, approximately 15 percent hydrogen and 85 percent carbon, which are burned in an excess of air or oxygen, then there is considerable CO_2 in the hot exhaust gases. The CO_2 molecule possesses a very strong radiating band centered around 4.3 micrometers. The radiation arising from this vibration-rotation band of CO_2 therefore represents the major source of plume emission in the mid-infrared spectral region.

The ultimate objective of the overall program is to be able to determine the radiant energy available to a remote sensor from a particular target or class of targets operating under a specified set of arbitrary conditions. This overall problem then readily divides into three distinct phases: (1) flow field description of the hot gaseous plume, (2) radiation model describing the emission characteristics of this gaseous environment, and (3) atmospheric modification to this radiated energy. The second and third phases have been previously reported [1-4] on and will not be considered here in any depth.

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*The results of the initial phase of this work are reported in a previous work [1], which discusses the first phase of the study leading to the development of a general spectral emissivity model for carbon dioxide.

This discussion will be largely concerned with that portion of the program which describes the method of coupling the flow field description of the plume with the radiation model. In particular, the flow field description, which provides the temperature and concentration profiles for the radiating specie, simply serves as an input to the radiation model which in turn is capable of describing the spectral and spatial emission characteristics of the gaseous jet plume. An outline of the approach that has been taken is shown in Figure 1.

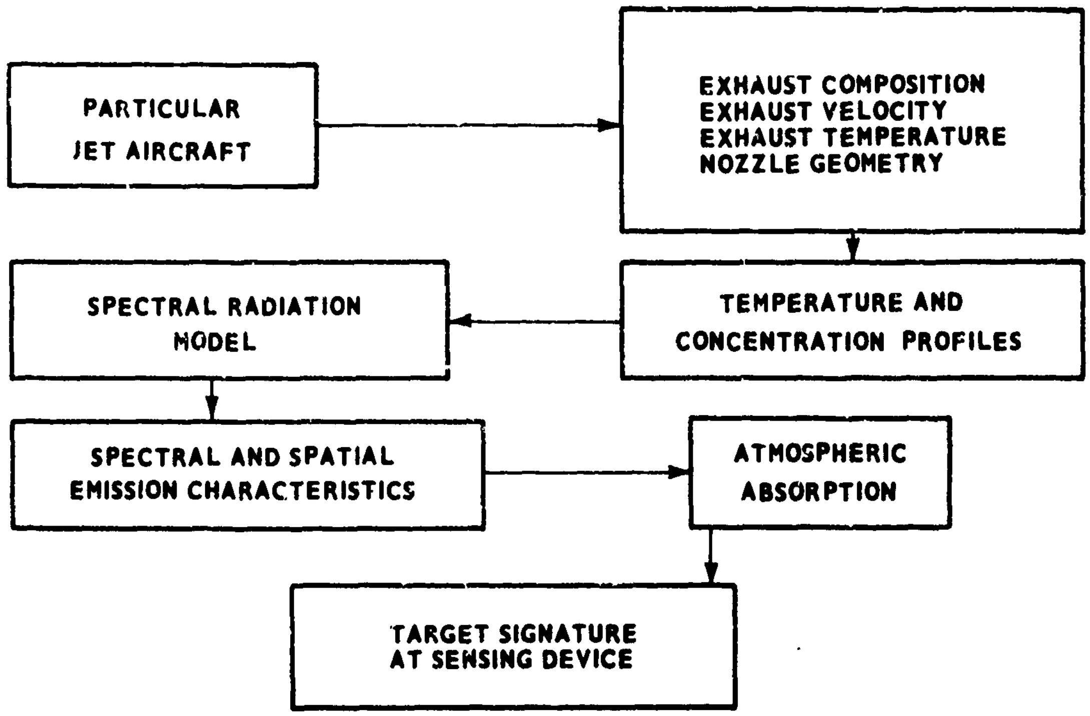

FIGURE 1. APPROACH OUTLINE

Section II. JET FUELS

Jet fuels consist primarily of hydrocarbons with only small amounts of other elements or compounds such as nitrogen, oxygen, sulphur and water. These non-hydrocarbons are generally controlled very carefully to rather exacting specifications for the various commercial types of jet propulsion fuels. The total amount of these non-hydrocarbons generally does not exceed 1 percent of the fuel composition. Thus, for any practical calculation involving jet fuels, it can be assumed that the fuels consist only of carbon and hydrogen. Both turboprop and turbojet engines use the same types of fuels. These propulsion fuels can be divided into three main types [5]:

1) Aviation kerosenes which have boiling temperatures in the range of 140° to 280°C. Such fuels with crystalline temperatures not higher than -60°C are considered excellent jet fuels. They possess high heats of combustion, low saturated vapor pressures, and good viscosity characteristics which ensure normal functioning of the jet engine under a rather wide range of operating conditions.

2) Wide range distillate fuels which include gasoline, kerosene, and ligroine fractions and have boiling temperatures in the range of 60° to 280°C. This type of fuel is highly volatile and generally possesses a high saturated vapor pressure. This causes high altitude operating difficulties because of vaporization and boiling.

3) Heavy petroleum fractions which have a low vapor pressure. This type of fuel is used principally for supersonic flight speeds and in naval aircraft and training aircraft because of its very high flash point.

Table I lists the most common jet fuels used in civilian and military aircraft.

The C:H ratios listed in Table I were estimated from the empirical relationship[5]

$$H\% = 26 - 15\rho^{15} \quad , \tag{1a}$$

and

$$C\% = 100 - H\% \quad , \tag{1b}$$

where ρ^{15} is the density of the jet fuel at 15°C in g/cm^3. The normalized compositions were then derived by assuming the total molecular weight to be

TABLE I. JET FUELS

Designation	Country	Type	Measured Density (g/cm³)	Density Specification (g/cm³)	Heat of Combustion (kcal/kg)	Normalized Composition $C_x H_y$		C:H Weight Ratio
						X	Y	
[illegible]-1	U. S. S. R.	1	0.815*	0.800-0.850*	10,250	7.18	13.7	6 26
TS-1	U. S. S. R.	1	0.785*	> 0.775*	10,250	7.14	14:1	6.03
T-2	U. S. S. R	2	0.760*	> 0.775*	10,250	7.11	14.5	5.85
JP-1B	U. K.	1	0.785*	0.785-0.825**	10,280	7.14	14.1	6.03
JP-4B	U. K.	2	0.751*	0.750-0.80[illegible]**	10,280	7.10	14.6	5.78
JP-5B	U. K.	1	-	0.780-0.850**	10,300	-	-	-
JP-1	U. S. A.	1	0.804**	0.780-0.850**	10,300	7.17	13.8	6.17
JP-3	U. S. A.	2	0.792**	0.740-0.780**	10,270	7.15	14.0	6.08
JP-4	U. S. A.	2	0.764*	0.750-0.802**	10,400	7.12	14.4	5.88
JP-5	U. S. A.	3	0.831*	0.780-0.845**	10,253	7.20	13.4	6.39
Air-3405	France	1	-	Not standardized	10,150	-	-	-
Air-3407	France	2	-	0.740-0.825*	10,200	-	-	-

* 20°C
** 15.5°C

100 g/g-mole. In general, the C:H ratio increases somewhat with the heaviness of fractional composition and as the C:H ratio increases, the amount of air required for complete combustion decreases. The amount of air required for the complete combustion of a quantity of fuel is easily calculated, and for most jet fuels, the ratio varies from 14 to 15 units of air to one unit of fuel. This can be illustrated by computing the mass of air required for the complete combustion of a unit mass of fuel. One may consider a hydrocarbon of the form C_xH_y and assume that air is composed only of nitrogen and oxygen. This is reasonable, since the atmosphere is composed of the following major constituents.

TABLE II. ATMOSPHERIC COMPOSITION

Specie	Mole Percent
Nitrogen	78.09
Oxygen	20.95
Argon	0.93
Carbon dioxide	0.03
Hydrogen	0.01

This shows that nitrogen and oxygen compose over 99 percent of the atmosphere by volume. It can therefore be assumed that the oxidizer is of the form N_AO_B. For the temperatures and pressures encountered in a typical jet engine, nitrogen acts only as an inert specie. Therefore, the following burning or combustion process may be considered:

$$C_xH_y + (X + Y/4)O_2 \rightarrow XCO_2 + (Y/2)H_2O \quad . \tag{2}$$

The mass of oxygen required for complete combustion of a unit mass of fuel is then given by

$$\frac{\text{Mass oxygen}}{\text{Mass fuel}} = \frac{(2X + Y/2)M_O}{XM_C + YM_H} \quad , \tag{3}$$

where M_i represents the molecular weight of the i^{th} specie. In order to compute the mass of air required, then it is only necessary to divide the above expression by the mass fraction of oxygen occurring in the atmosphere. This is readily obtained by multiplying the mole fraction listed in Table II by the ratio of the molecular weight of oxygen to the mean molecular weight of the

atmosphere. This gives 23.2 percent by weight for oxygen. Thus the mass of air required for complete combustion of a unit mass of fuel is given by

$$\frac{\text{Mass air}}{\text{Mass fuel}} = \frac{1}{0.232}\left\{\frac{(2X + Y/2)M_O}{XM_C + YM_H}\right\} . \tag{4}$$

In general, for the jet engine type of problem being discussed, an excess air factor is used to limit the temperature of the gases entering the turbine. This factor is generally of the order 3.8 to 4.0. However, at this point, the oxidizer (air) to fuel ratio can be simply denoted as O/F, and this can be treated as a parameter. The composition of the combustion products can now be obtained by first computing the coefficients A and B for the atmospheric composition $N_A O_B$. As previously noted, the mass fraction of oxygen is 0.232 and can be computed from the composition $N_A O_B$ by the expression

$$f_O = 0.232 = \frac{BM_O}{BM_O + AM_N} . \tag{5}$$

The term "B" is uniquely defined by assuming 100 as the denominator. A similar calculation for nitrogen gives the result

$$N_A O_B = N_{5.48} O_{1.45} . \tag{6}$$

The composition of the product constituents can now be obtained from the reaction

$$(O/F) N_A O_B + C_x H_y \rightarrow XCO_2 + (Y/2)\ H_2O$$

$$+ \{(B/2) O/F - X - Y/4\}\ O_2 + (A/2)(O/F) N_2 . \tag{7}$$

If it is now assumed that a unit mass of fuel is being consumed, then the mass of the exhaust products, W_i, can be written from the above equation, i.e.,

$$W_{CO_2} = \frac{X\left(M_C + 2M_O\right)}{XM_C + YM_H} , \tag{8}$$

$$W_{H_2O} = \frac{Y\left(2M_H + M_O\right)}{2\left(XM_C + YM_H\right)} , \tag{9}$$

$$W_{O_2} = \left\{\frac{B(O/F) - 2X - Y/2}{XM_C + YM_H}\right\} M_O \quad , \tag{10}$$

$$W_{N_2} = \frac{A(O/F)M_N}{XM_C + YM_H} \quad . \tag{11}$$

For unit mass of fuel, a mass of O/F units of air is assumed to be consumed so that a total of (1 + O/F) units is involved in the reaction. The mass fraction of each product specie, α_i, is then given by simply dividing the exhaust product constituent mass by the total mass. Thus

$$\alpha_i = \frac{W_i}{\Sigma W_i} = \frac{W_i}{1 + O/F} \quad , \tag{12}$$

so that the mass fraction of CO_2, for example, contained in the exhaust products after combustion is given by

$$\alpha_{CO_2} = \frac{X\left(M_C + 2M_O\right)}{\left(XM_C + YM_H\right)(1 + O/F)} \quad . \tag{13}$$

Since the mole fraction of the combustion products is also of concern, particularly if concentrations are expressed in partial pressures, then it will be useful to consider the relationship between mass fraction, α_i, and mole fraction, β_i. For an ideal gas mixture in thermal equilibrium, the total pressure can be written as $P_T \propto \eta_T$, where η_T is the total number of moles and understood to be the weight of the gas divided by the mean molecular weight. If the total pressure of the gaseous misture is now taken to be the sum of the partial pressures present in the mixture, then for each constituent the partial pressure is $P_i \propto \eta_i$. Thus

$$P_i = P_T\left(\eta_i/\eta_T\right) = P_T\beta_i \quad , \tag{14}$$

or

$$P_i = P_T\left(\frac{W_i}{M_i}\frac{M_T}{W_T}\right) = P_T\alpha_i\frac{M_T}{M_i} \quad . \tag{15}$$

Equating these two equations yields the desired relationship, namely

$$\beta_i = \alpha_i \frac{M_T}{M_i} \quad , \tag{16}$$

where M_T is the average molecular weight of the gaseous mixture which is easily shown to be

$$M_T = \frac{1}{\Sigma\alpha_i/M_i} \quad , \tag{17}$$

where the sum extends over the number of gases present in the mixture. Thus for any specie within the mixture, the relation between the mass fraction and mole fraction is

$$\beta_i = \frac{\alpha_i}{M_i} \frac{1}{\Sigma\alpha_i/M_i} \quad . \tag{18}$$

Substitution of previously defined quantities into the above expression yields

$$\beta_{CO_2} = \frac{4X}{Y + 2(O/F)(A + B)} \quad , \tag{19}$$

$$\beta_{H_2O} = \frac{2Y}{Y + 2(O/F)(A + B)} \quad , \tag{20}$$

$$\beta_{N_2} = \frac{2A(O/F)}{Y + 2(O/F)(A + B)} \quad , \tag{21}$$

$$\beta_{O_2} = \frac{2B(O/F) - 4X - Y}{Y + 2(O/F)(A + B)} \quad . \tag{22}$$

The results of the preceding discussion can be illustrated by considering a specific example. The common hydrocarbon fuel CH_2 may be considered which has a C:H ratio of 5.96 and consists of 14.4 percent hydrogen and 85.6 percent carbon. Normalizing the molecular weight to a value of 100 gives a chemical formula of $C_{7.13}H_{14.3}$. The mass of oxygen required for complete combustion of a unit mass of fuel is given by equation (3),

$$\frac{\text{Mass oxygen}}{\text{Mass fuel}} = \left(\frac{14.26 + 7.15}{100}\right)16.0 = 3.43 \quad .$$

The mass of air required for the combustion process is given by equation (4) and obtained by dividing the above number by 0.232:

$$\frac{\text{Mass air}}{\text{Mass fuel}} = \frac{3.43}{0.232} = 14.8 \quad .$$

Using an excess air factor of four then gives an oxidizer to fuel ratio of 59.2. Since this occurs as a parameter in determining the concentration of the product constituents, an O/F ratio of 60 will be used. The mass fraction of each of the product species is then given by equation (12). Substituting into this set of equations yields the following:

Product	Mass Percent
CO_2	5.14
H_2O	2.11
O_2	17.20
N_2	75.51

Equation (17) can then be used to compute the average molecular weight of the product gas mixture. This yields $M_T = 28.85$. Equations (16) or (19) through (22) then give:

Product	Mole Percent
CO_2	3.37
H_2O	3.38
O_2	15.51
N_2	77.74

Finally, it will be pointed out that the CO_2 concentration present in the exhaust products as computed above is approximately 100 times the normal atmospheric concentration of CO_2. The mole percent or percent by volume of the constituents, when expressed as a fraction, also gives the partial pressure of the specie when the total pressure of the gaseous mixture is one atmosphere [equation (14)]. Figure 2 shows the mole percent of CO_2 contained in the exhaust products as a function of C:H with air to fuel ratio expressed as a parameter.

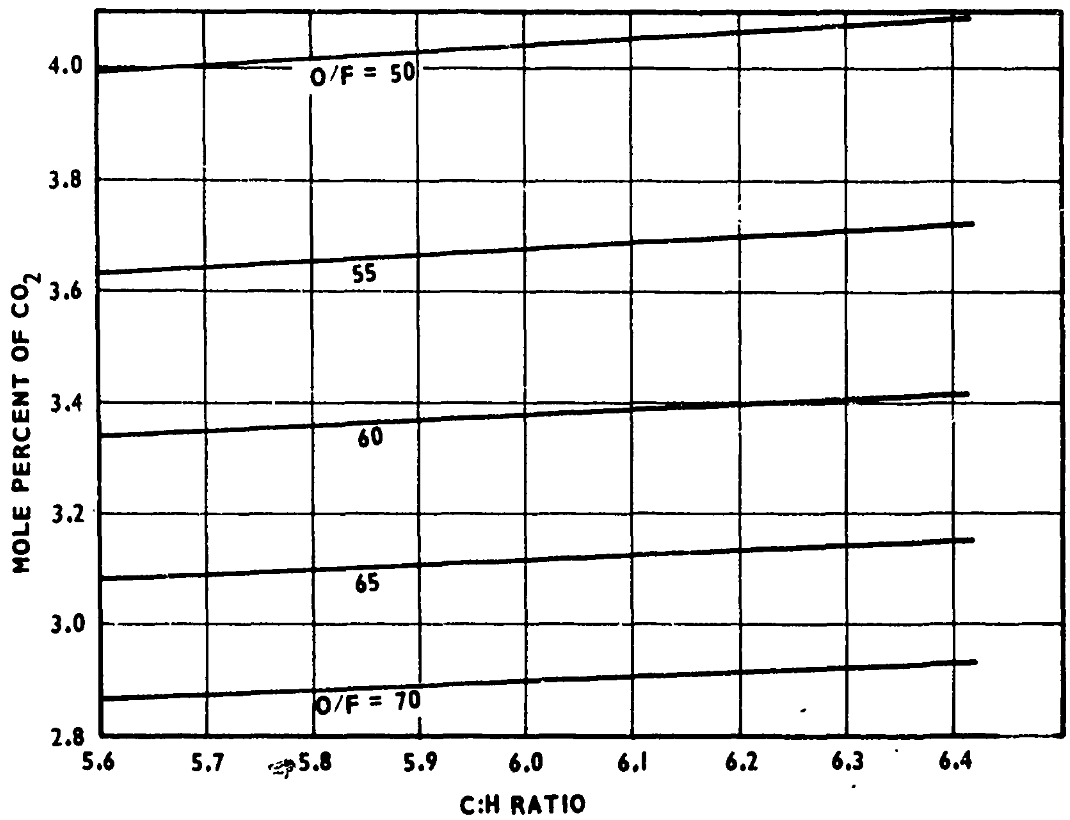

FIGURE 2. MOLE PERCENT OF CO_2 CONTAINED IN EXHAUST PRODUCTS AS A FUNCTION OF CARBON TO HYDROGEN FUEL WEIGHT RATIO WITH OXIDIZER TO FUEL RATIO AS A PARAMETER

Section III. FLOW FIELD

The flow field or plume model must be capable of generating the temperature and specie concentration within the exhaust plume as a function of the initial values at the tailpipe exit plane and the ambient conditions. Figure 3 depicts a typical jet plume along with the objective of the plume or flow field model. An axisymmetric coordinate system is used to define any point within the plume. The coordinate X measures the downstream position from the exit plane of the nozzle or tail pipe and the coordinate R measures the radial position or distance normal to the symmetry axis within the plume. The plume is divided into two regions called the core and developed or mixing regions. The core of the plume is a region of constant velocity and thermodynamic properties, whereas the developed portion of the plume is that region where the plume possesses property gradients in both the axial and radial directions. This model is a finite difference flow field program which takes the conditions at the exit nozzle; velocity, pressure, temperature, specie or constituent concentration, nozzle size, and ambient or free stream conditions, and then computes the temperature and specie concentration throughout the plume.

OBJECTIVE: TO DETERMINE THE PLUME SPREADING CHARACTERISTICS, IN PARTICULAR THE AXIAL AND RADIAL TEMPERATURE - COMPOSITION DECAY RELATIONSHIPS FROM A KNOWLEDGE OF THE GEOMETRY AND EXIT CONDITIONS OF THE NOZZLE.

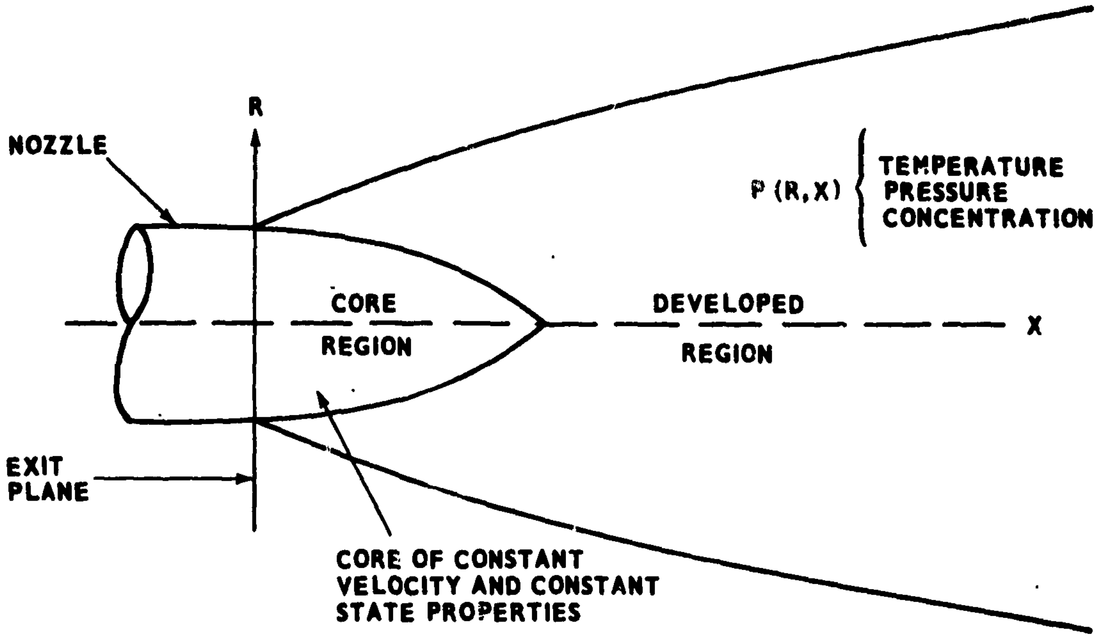

FIGURE 3. PLUME MODEL AND OBJECTIVE

The primary problem is to consider the mixing of two streams which are taken to be parallel but which possess different velocities, temperatures, and chemical compositions. Only the basic features of the physical problem will be mentioned in this limited discussion. These features can be outlined by considering a fully expanded axisymmetric jet exhausting into a uniform unbounded parallel stream. This is shown in Figure 4 where it is assumed that the pressures of the two streams are the same. The transport mechanisms that take place between the two streams include the transfer of momentum, the conduction of heat, and the diffusion of species causing the two streams to mix. In the region downstream of the jet exit plane, three distinct regions exist. In regions I and II, the two streams retain their original properties. Region III contains a mixture of the two streams resulting in nonuniform temperature, velocity, and specie concentration profiles. The mixing process tends to reduce the difference in the properties of the two streams. The flow itself can be either laminar or turbulent, and the analysis of either can be accomplished by considering only changes in the mathematical description of the expressions for the transport coefficients.

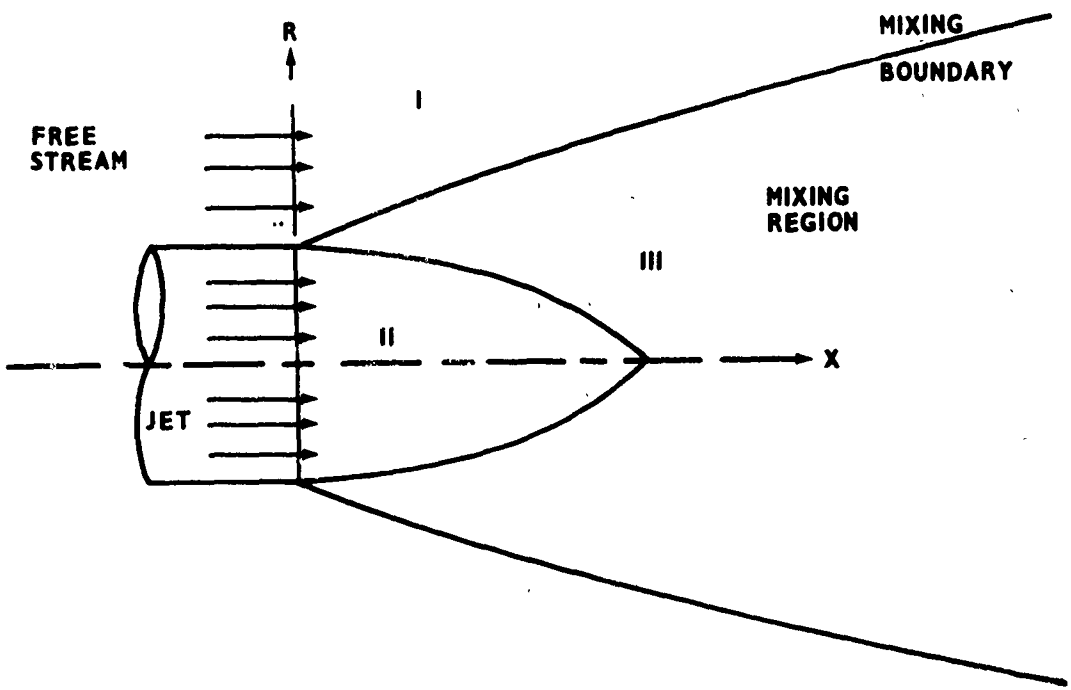

FIGURE 4. DISTINCT PLUME FEATURES

For the systems under consideration, both the pressure and temperature are relatively low. This results in the reaction time being much longer than

the flow time so that mixing occurs before any reaction takes place [6]. This frozen type flow can be analytically described by utilizing appropriate transport coefficients, an equation of state, expressions describing the temperature dependence of the species specific heat and enthalpy, and the conservation equations for continuity, energy, momentum and species. A lack of basic knowledge concerning the turbulent transport properties forces one to rely heavily on experimental data for the eddy viscosity, eddy conductivity (Prandtl number) and diffusion coefficient (Lewis number). The most difficult problem was the adoption of a satisfactory eddy viscosity model to use in the basic numerical program. A considerable amount of effort was expended to achieve a satisfactory viscosity model for incorporation into the flow program.*

Typical results from the program are shown in Figures 5 through 9. Figure 5 shows the axial values of the temperature and velocity decay for a particular jet engine compared with the manufacturer's data. This is for a compressible axially symmetric free turbulent jet exhausting into quiescent air at sea level conditions. Results for an inflight aircraft are shown in Figures 6 through 9. Figure 6 shows the decay of the temperature and CO_2 concentration along the symmetry axis. This aircraft has a turbojet engine and is assumed to be flying at sea level conditions with a speed of 280 meters per second. The top curve is a normalized plot of how the temperature varies with downstream distance along the symmetry axis. The ordinate is the ratio of the axial temperature to the temperature at the tailpipe exit. At a downstream distance of 35 feet the temperature has decayed by a factor of approximately 2.5. The dotted line shows the ambient temperature ratio and at 35 feet downstream the axial temperature is 25 to 30 percent above ambient temperature. The lower curve in Figure 6 shows a normalized plot of how the CO_2 concentration varies with downstream distance along the symmetry axis. The ordinate is the ratio of the CO_2 concentration along the symmetry axis to the concentration of the tailpipe exit. This represents a concentration which is 105 times the atmospheric CO_2 concentration (0.33 percent by volume). At a distance of 35 feet downstream the concentration has decayed to within 10 to 15 percent of the ambient value. Figures 7 and 8 show the radial distribution of the temperature and CO_2 concentration at selected axial positions. These clearly depict the diminishing core and appearance of the mixing region as a function of downstream distance. The ordinate in both plots is the ratio of the plume property to the free stream property. Figure 9 shows particular isotherms and the core region (shaded) for the same plume.

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* This basic program was supplied to the author by Dr. A. Ferri and Dr. P. Baronti of Advanced Technology Laboratories, Inc., 400 Jericho Turnpike, Jericho, New York 11753.

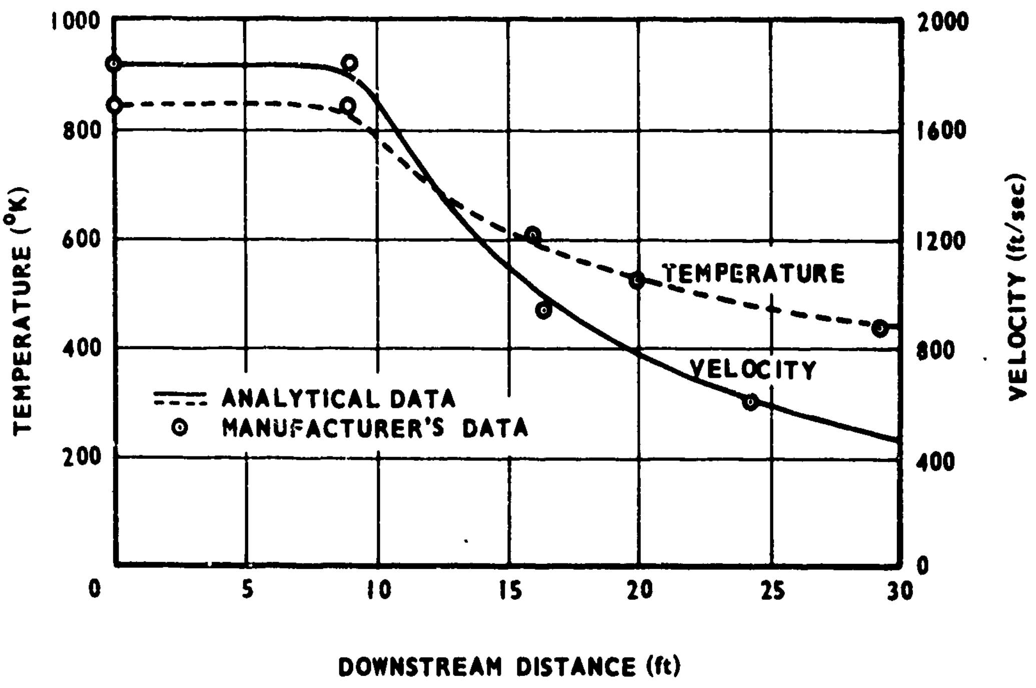

FIGURE 5. COMPARISON OF PLUME FLOW FIELD ANALYTICAL MODEL WITH MANUFACTURER'S DATA FOR A PARTICULAR JET ENGINE

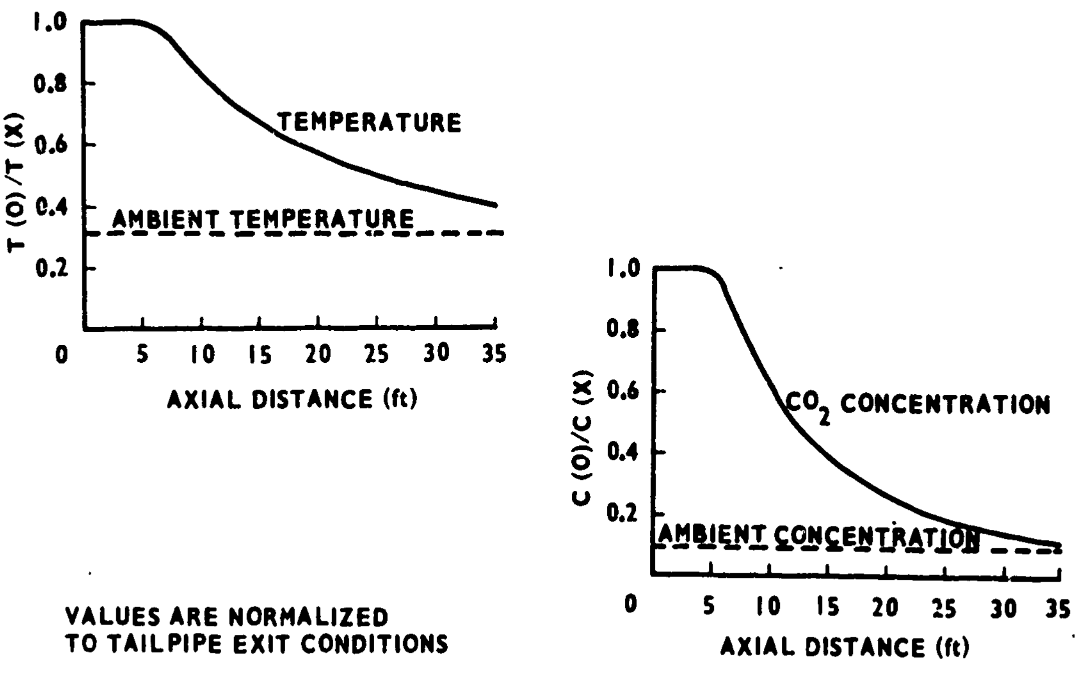

FIGURE 6. AXIAL DECAY OF TEMPERATURE AND CO_2 CONCENTRATION

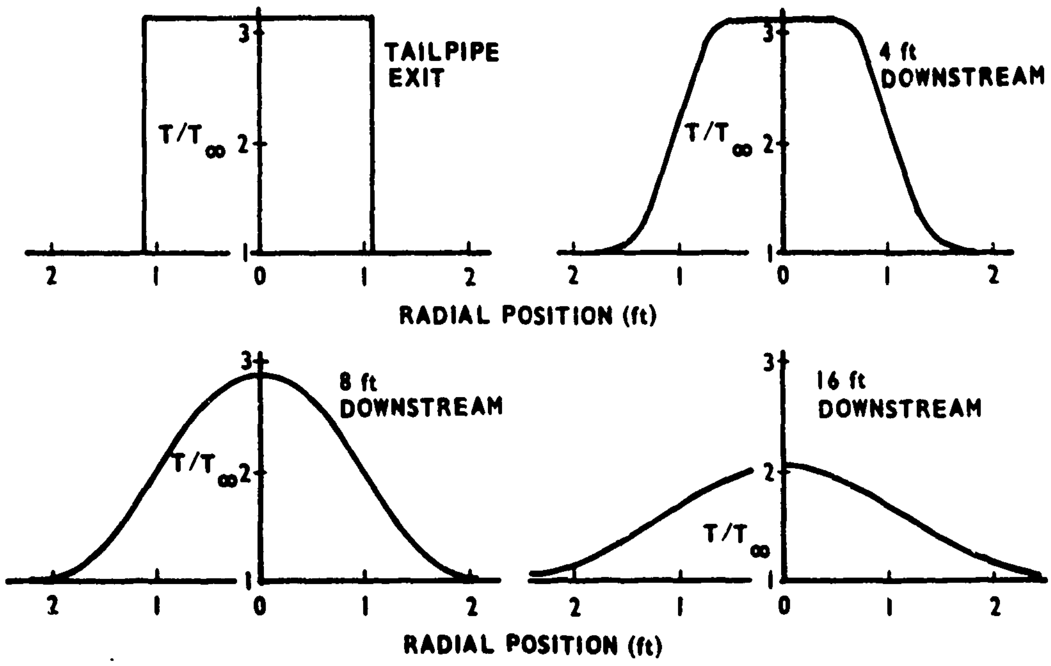

FIGURE 7. RATIO OF PLUME TO AMBIENT TEMPERATURE VERSUS RADIAL POSITION WITH DOWNSTREAM POSITION AS A PARAMETER

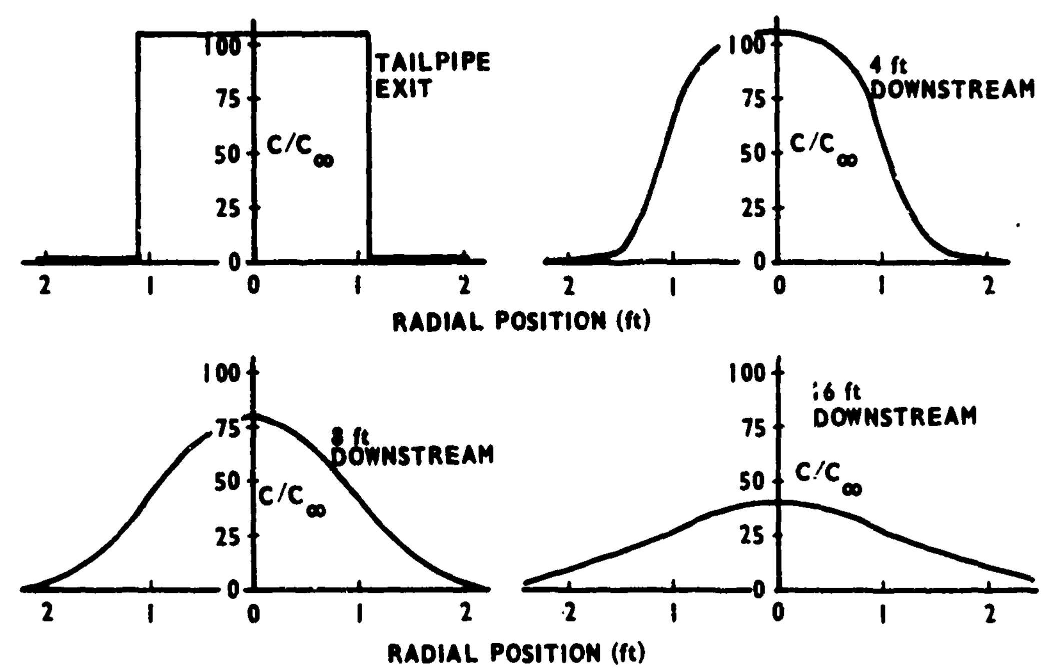

FIGURE 8. RATIO OF PLUME TO AMBIENT CO_2 CONCENTRATION VERSUS RADIAL POSITION WITH DOWNSTREAM POSITION AS A PARAMETER

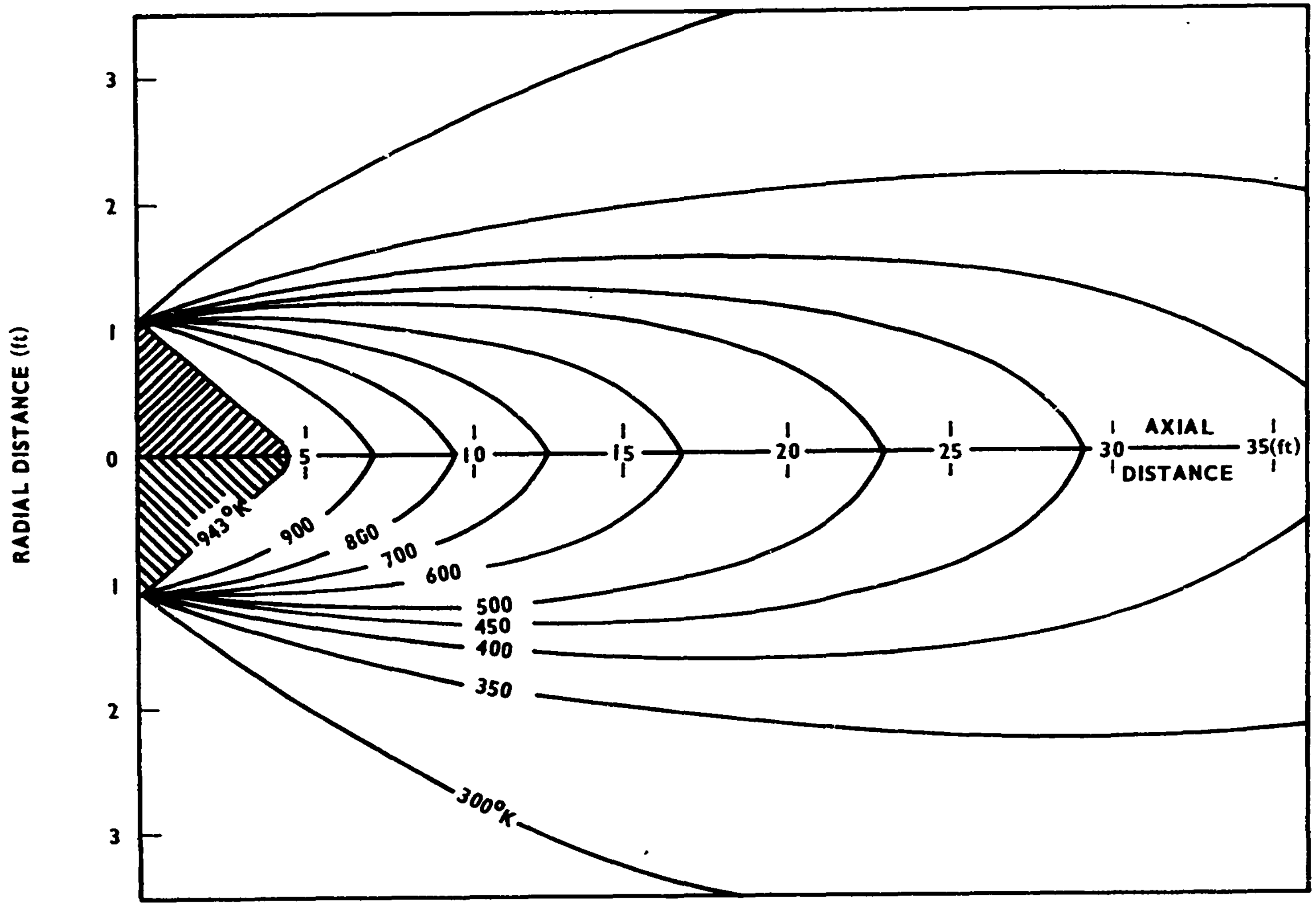

FIGURE 9. ISOTHERMS FOR AN INFLIGHT PLUME

The Advanced Technology Laboratories generalized frozen mixing program [6] is written in Fortran IV and can be used on any large scale computing system. The input instructions, a listing of the program, a typical set of input data and a sample of the subsequent output are included in the appendix.

Section IV. RADIATION CALCULATIONS

After the flow field calculations have been made for a particular aircraft, the radiation calculations may be started. The mathematical details and description of the radiation model have previously been reported on [1]. Figure 10 shows the geometry which is used for making the radiation calculations. The plume is depicted simply as a truncated ice cream cone. The outer edge of the plume is defined by the isotherm $T/T_\infty = 1.05$. This was found necessary, particularly for a jet exhausting into quiescent air, because of the slow exponential of the plume width in the radial direction.

A direction is then chosen in which it is desired to make the radiation calculations. This direction is indicated by α and called the aspect angle. A plane is then set up to cut the plume in this direction. The aspect angle is the angle between the symmetry axis and the direction that is chosen to make the radiation calculations. Zero degrees is the direction indicated by looking downstream along symmetry axis, 90 degrees is looking normal to the symmetry axis, and 180 degrees is looking upstream along the symmetry axis. Within this plane, various parallel lines of sight are constructed for actually making the radiation calculations. The coordinate Z_0 measures the distance of the line of sight above a line in the plane which intersects the symmetry axis. The distance measured along a particular line of sight is indicated as ℓ. The $\ell = 0$ point is where the line of sight first intersects the plume surface The coordinate X_0 measures the downstream position where the calculation is being made and R_0 is the radius of the plume at this point.

Next the coordinates (X, R) are computed as a function of ℓ, Z_0, α, X_0 and R_0 along the line of sight.

$$R = \left\{Z_0^2 + \left[\ell \sin \alpha - \sqrt{R_0^2 - Z_0^2}\right]^2\right\}^{1/2} \quad ,$$

$$X = X_0 + \ell \cos \alpha \quad .$$

The increment $\Delta\ell$ which divides the plume thickness into small segments is automatically calculated by the computer. The flow field data have been stored in the computer previous to calculating the coordinates (X, R) along the line of sight. A two-dimensional interpolation scheme is then used to calculate the plume properties along the line of sight. There is now a dimensional line segment, the length of which represents the plume thickness, with the temperature and concentration of the radiating specie specified along the line. The molecular band parameters are now computed at each specified point along the line segment. The emission calculations can now be made.

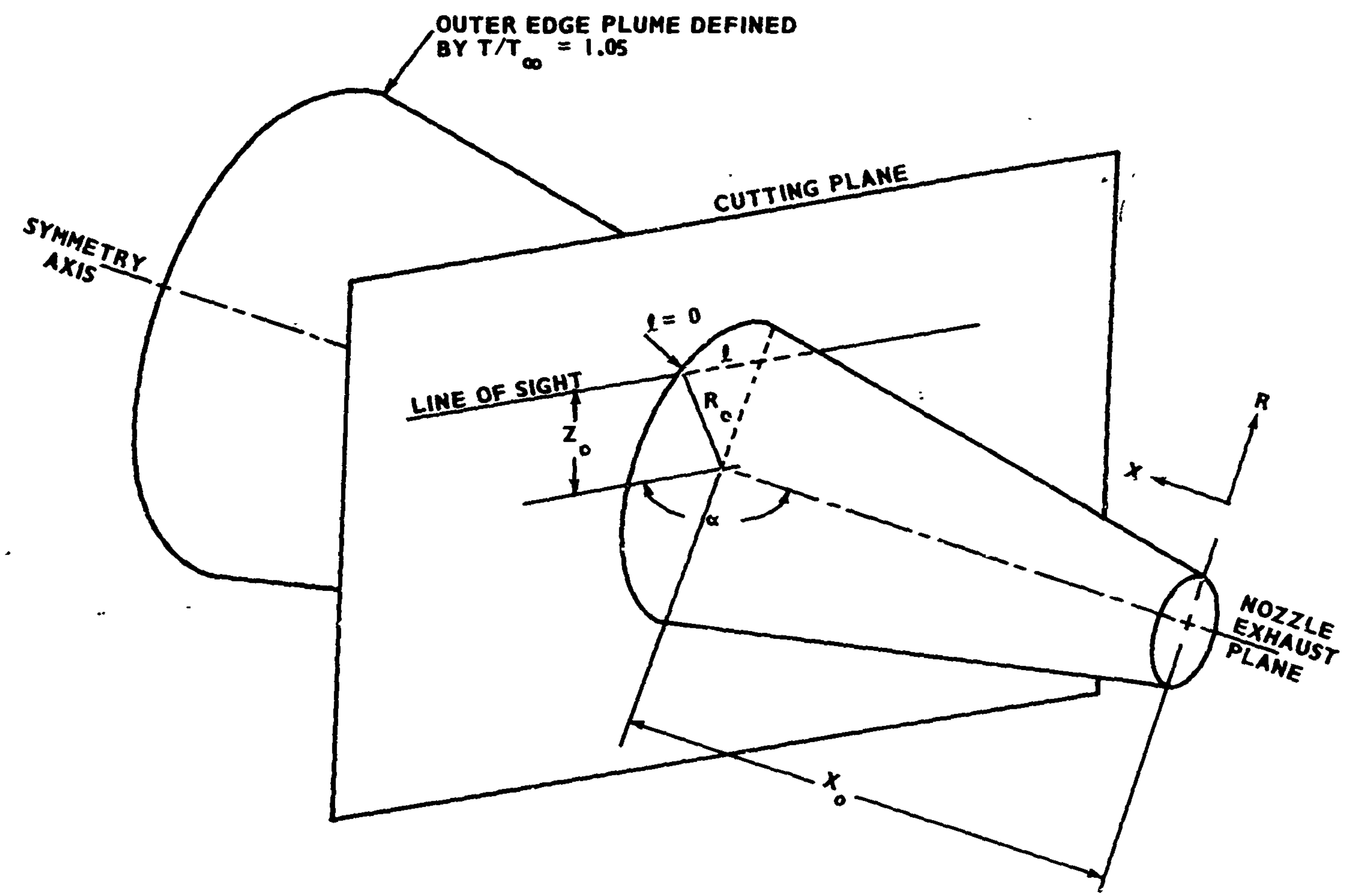

FIGURE 10. GEOMETRY FOR RADIATION CALCULATIONS

It is not an easy task to calculate accurately the radiation emitted from a homogeneous gas. The problem is obviously more complicated when dealing with an inhomogeneous gas. A modified form of the statistical band model has been chosen for making the emissivity calculations. For the inhomogeneous calculations this was further modified by using a method similar to the Curtis-Godson method. This method takes inhomogeneous gas which has a certain transmissivity and replaces it with a homogeneous gas which has the same transmissivity.

In this discussion only the results of the method will be outlined. The radiating band structure exhibited by the hot plume exhaust gases is actually composed of many closely spaced or overlapping spectral lines. In general, to calculated the emissivity of transmissivity of a gas, three parameters must be known for the absorbing or emitting molecule. The molecular band parameters are dependent on spectral location as well as the state of the gas. These three parameters are denoted as S, d, and γ where S is the average intensity of a spectral line, d is the spacing between lines, and γ is the line half-width. For the inhomogeneous calculations, these parameters are combined in a particular manner and an equivalent set of parameters is computed. These equivalent parameters are denoted by μ and ν and shown below.

$$\nu = \int_0^{Y(\ell)} \frac{S[\lambda, T(\ell)]}{d^2[\lambda, T(\ell)]} \gamma\left[P_e, T(\ell)\right] dY(\ell) \quad ,$$

$$\mu = \int_0^{Y(\ell)} \frac{S[\lambda, T(\ell)]\, dY(\ell)}{d[\lambda, T(\ell)]} \quad .$$

These parameters are computed in terms of the basic band parameters and a quantity denoted as Y which is referred to as the reduced optical path or equivalent gas thickness. The reduced optical path is defined as

$$Y(\ell) = \int_0^{\ell} \frac{P_{CO_2}}{P_{e(\ell)}} d\ell \quad ,$$

where ℓ represents the actual thickness of gas being considered, P_{CO_2} is the partial pressure of the absorbing gas, and P_e is the equivalent pressure. The equivalent pressure is defined by the relationship

$$P_e = P_t + b\, P_{CO_2} \quad ,$$

where P_t is the total pressure of the gaseous system, and b is a spectral broadening coefficient which depends on the overall gaseous composition.

The transmission of the plume along the chosen line of sight can now be computed as a function of plume thickness and spectral location λ:

$$\tau(\lambda, \ell) = \exp\left\{\frac{-2\nu}{\mu}\left(\sqrt{1 + \frac{\mu^2}{\nu}} - 1\right)\right\} .$$

This calculation is necessary since the radiation emitted from the interior of the plume must be transmitted through a portion of the plume. At this point the computer has available at each spectral point of interest the transmission along the line of sight ℓ. The plume thickness is now divided into a number of small segments of thickness $\Delta\ell_i$ (Figure 11). Average plume properties are assigned to each segment so that each segment can be considered as a homogeneous gas. The spectral emissivity is calculated for each homogeneous segment. This is computed from the equation

$$\epsilon_i(\lambda, \Delta\ell_i) = 1 - \exp\left\{\frac{-2\gamma(\bar{P}_e, \bar{T})}{d(\lambda, \bar{T})} \bar{P}_e\left[\sqrt{\frac{1 + S(\lambda, \bar{T})\, P_{CO_2} \Delta\ell_i}{\gamma(\bar{P}_e, \bar{T})\, \bar{P}_e}} - 1\right]\right\} ,$$

where all the quantities on the right hand side of the equation have previously been defined. The radiation emitted from a particular segment is then obtained by multiplying the emissivity by Planck's black body spectral emission function. This is then multiplied by the transmission factor to obtain the radiation emitted from the surface of the plume by the segment $\Delta\ell_i$. The result is indicated by $I_i(\lambda, 0)$ and given by the relationship

$$I_i(\lambda, 0) = \frac{\epsilon_i C_1 \lambda^{-5} \tau_i}{\pi\left[\exp(C_2/\lambda T) - 1\right]} .$$

This is repeated for all segments along the line of sight, and the results are then summed to obtain the spectral radiation from this one point on the plume at the spectral point λ. This procedure is repeated for each spectral point to get the spectral distribution of radiation, again from this particular point on the plume, in the direction of α. The whole set of computations is now repeated for several points on the plume surface in order to obtain the spatial distribution or the total radiation emitted from the plume in the direction of the aspect angle α:

$$I(\lambda, \alpha, X_0, Z_0) = \sum_i I_i \quad \left[W/(cm^2\text{-ster-}\mu m)\right]$$

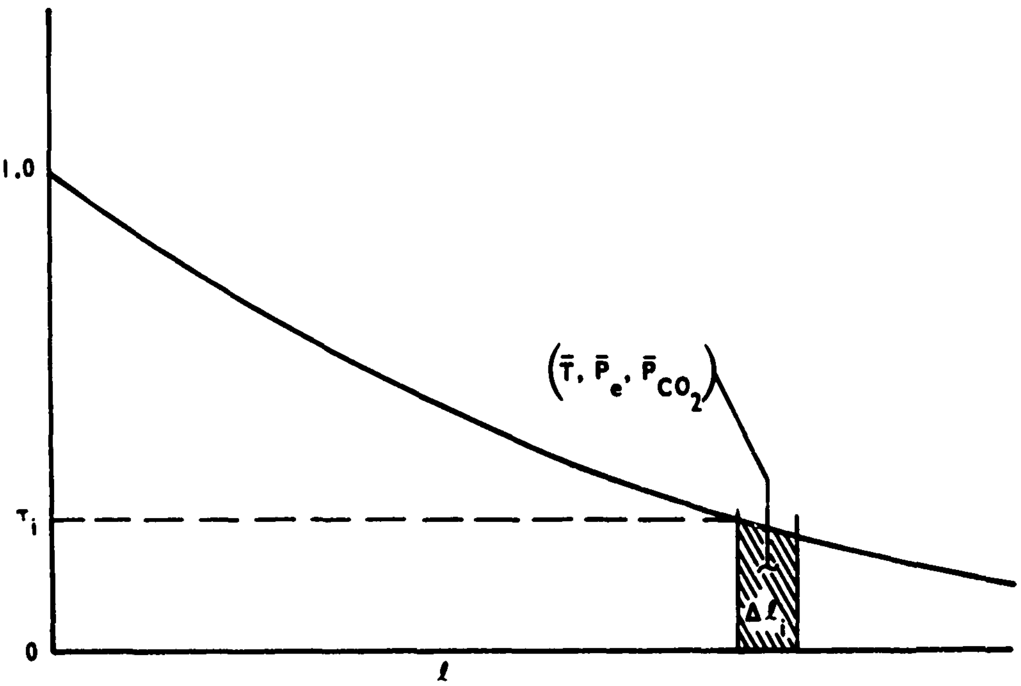

FIGURE 11. EMISSION MODEL

Figure 12 shows a comparison of the results of the homogeneous and non-homogeneous calculations for a particular homogeneous gas. This represents the spectral emissivity of a slice of gas taken at the exit plane of a typical exhaust nozzle.

Results from the program are shown in Figure 13. This is for an inflight aircraft and for the same aircraft operating in a tied-down or static position. Both curves are for seal level conditions and each is for a 90-degree aspect angle. Again this is for a typical jet aircraft. The emitted radiation has been integraded over the surface of the plume so each curve gives the spectral distribution of the plume emission.

It is interesting to note that the radiation emitted from the aircraft in a static position is larger than that emitted from the inflight aircraft. The 280-meter per second curve has a peak value of 1770 watts per steradian-micrometer whereas the static curve reaches a peak of 2300 watts per steradian-micrometer. This is apparently due to the free stream air which cools and reduces the size of the plume. This is also indicated by considering the area under each curve which represents the total emitted radiation. These values are indicated by Figure 13, where it can be seen that the static value is approximately 30 percent less than the inflight value.

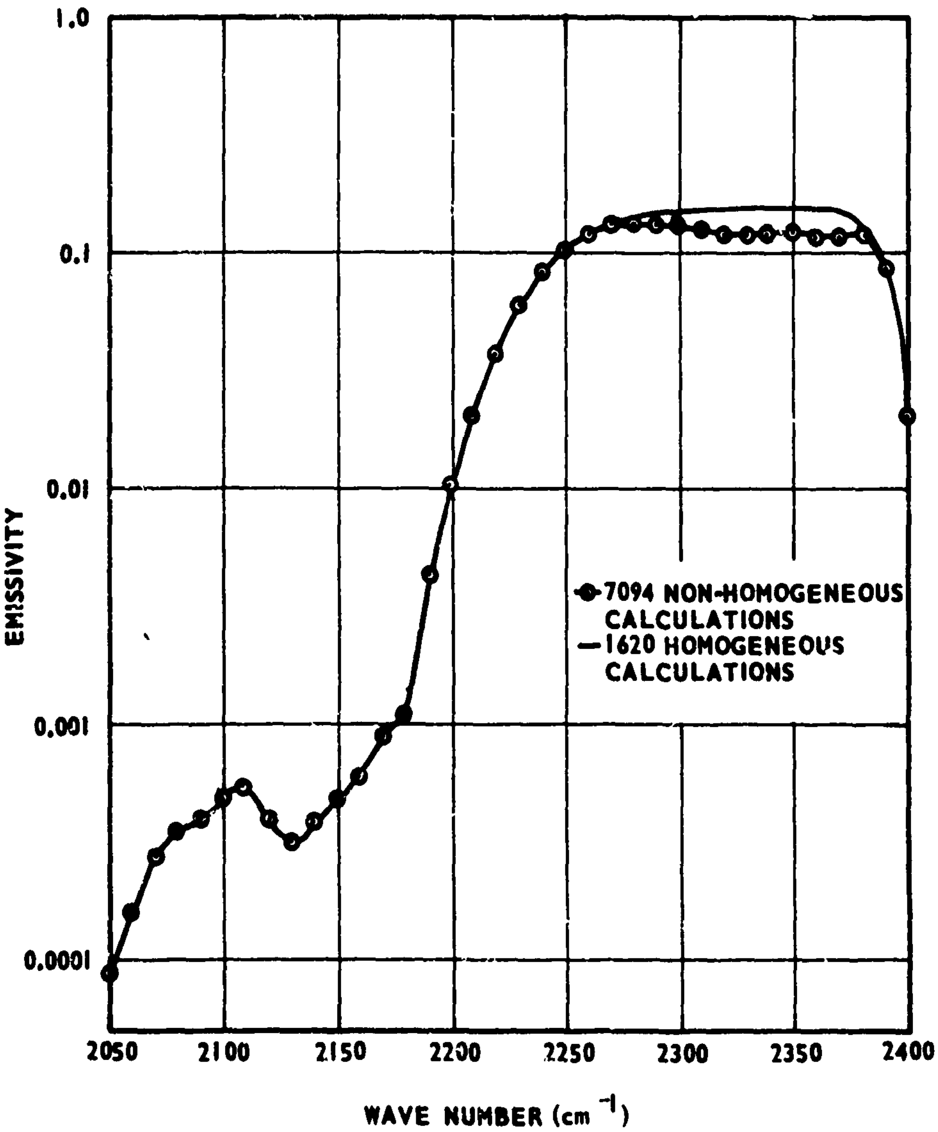

FIGURE 12. COMPARISON OF HOMOGENEOUS AND NON-HOMOGENEOUS CALCULATIONS

The absorption dips occurring in each curve are due to the cooler outer extremities of the plume absorbing the radiation from the hotter interior. This effect is more pronounced for the static curve since the plume is larger in size. The small peaks seen beyond 4.8 micrometers are due to a much weaker CO_2 band centered in this region.

Figure 14 shows data for the same inflight aircraft that was discussed in Figu~e 13. Again this is for a 90-degree aspect. The results are presented

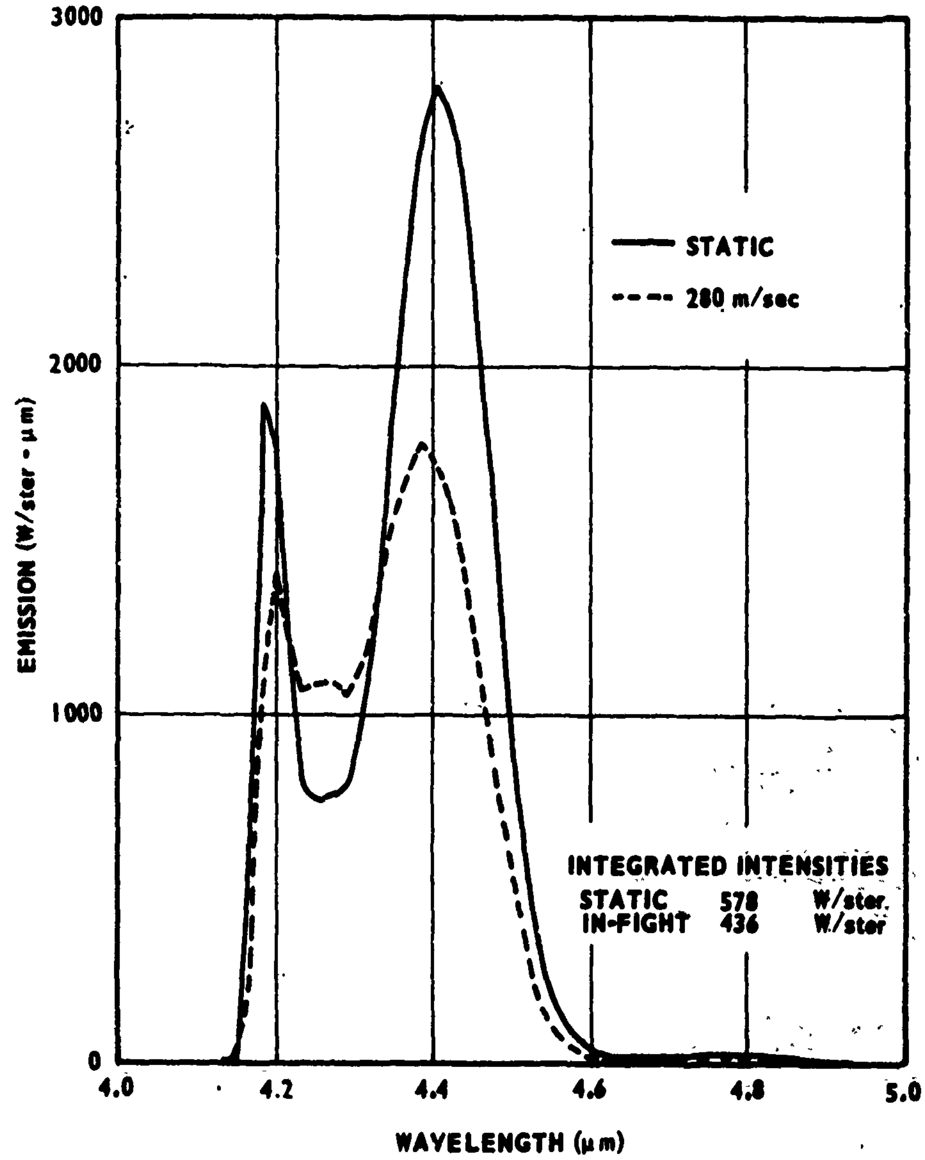

FIGURE 13. TYPICAL TURBOJET PLUME SURFACE EMISSION AT 90-DEGREE ASPECT

in a different manner, in that the spatial distribution was not integrated over the whole surface of the plume but only over the radial coordinate and then integrated over the spectral region. The result gives the axial decay of the radiation or the radiation per unit length of plume. This permits the radiation centroid to be calculated which is also shown in Figure 14. The plume geometrical centroid is about 7 feet aft of the tailpipe for this particular aircraft.

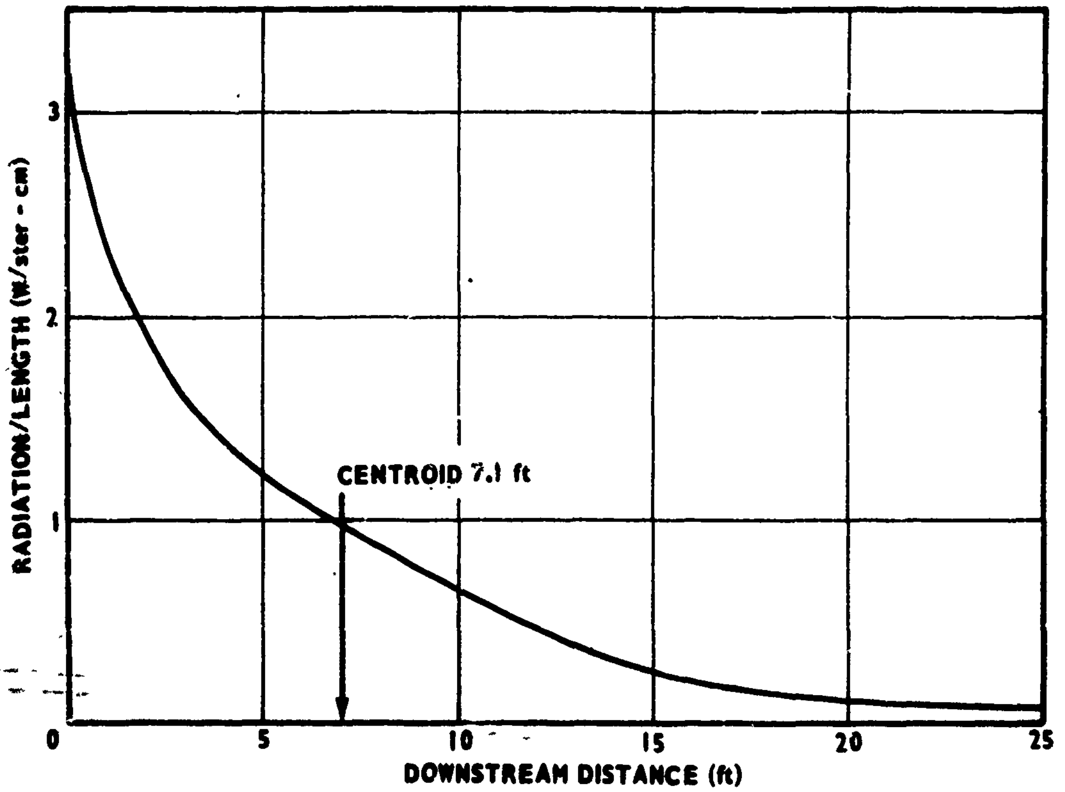

FIGURE 14. AXIAL DECAY OF PLUME RADIATION FOR A TYPICAL TURBOJET

One of the major objectives of this effort is to be able to predict the radiant energy that is emitted from a jet aircraft and is available to a remote sensor. This implies that the signature must be propagated through the atmosphere which, in reality, acts as an attenuation filter. Therefore an atmospheric transmission model [3] has also been developed in order to determine the atmospheric modification to the emitted energy. It is a two-component model that was derived from the well-known experimental data of Taylor and Yates. Molecular absorption of H_2O was considered along with other constituents of constant concentration such as CO_2, N_2O, CH_4 and CO. The constituents of constant concentration were combined into a single species, XO_2. The amount of XO_2 was chosen to be 32 atm cm/km, which is the average concentration of CO_2. Figure 15 shows a comparison of the transmission model with a set of independent measured transmission data. It can be seen that the computer model matches the measured data quite nicely. The broad absorption dip between 4.2 and 4.45 micrometers is due to CO_2 absorption. The dip at 4.5 micrometers is due to N_2O, and the fine structure is due primarily to H_2O.

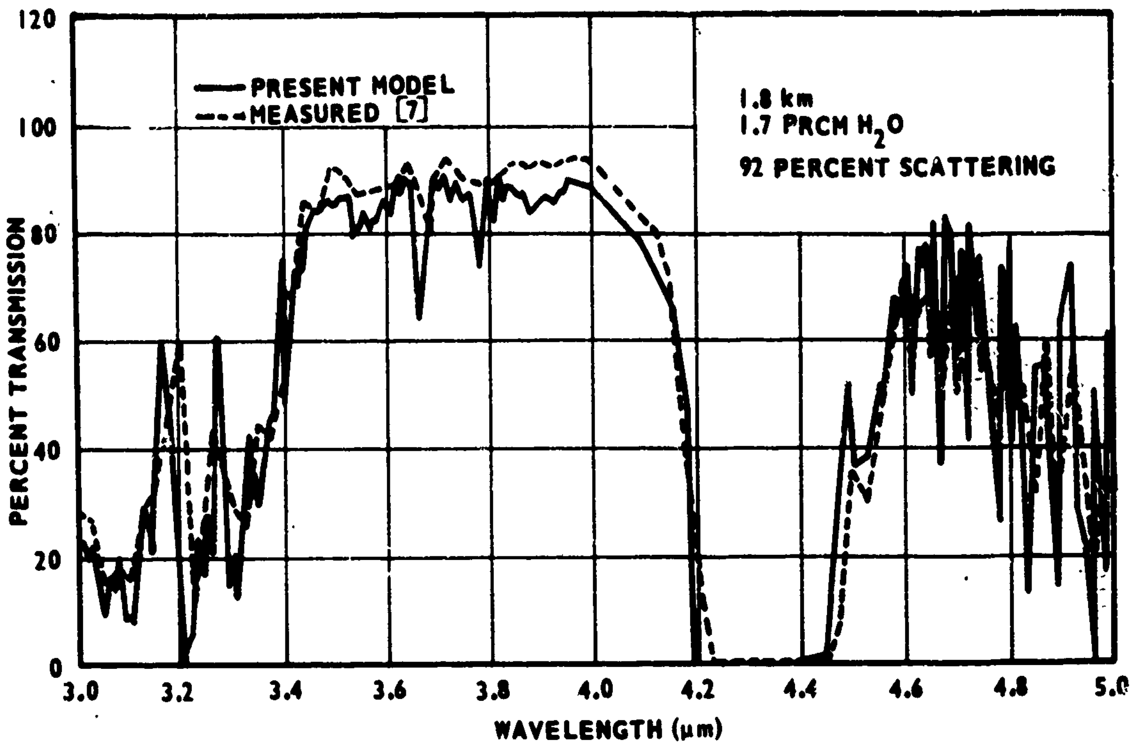

FIGURE 15. COMPARISON OF ATMOSPHERIC TRANSMISSION MODEL WITH MEASURED DATA

Figure 16 shows a typical plume signature put through 1, 7, and 15 kilometers of atmosphere by using the previously described transmission model. This shows the importance of the wings or skirts of the emission band since the center of the band gets completely absorbed in relatively short path lengths.

A comparison of the results of the present model with measured data is shown in Figure 17. This is for a particular jet aircraft operating in a static position at 100-percent power. The aspect angle is 10 degrees and the measured data were recorded at 1 mile from the aircraft. The theoretical results were put through the above described atmospheric transmission model to obtain the signature shown in Figure 17.

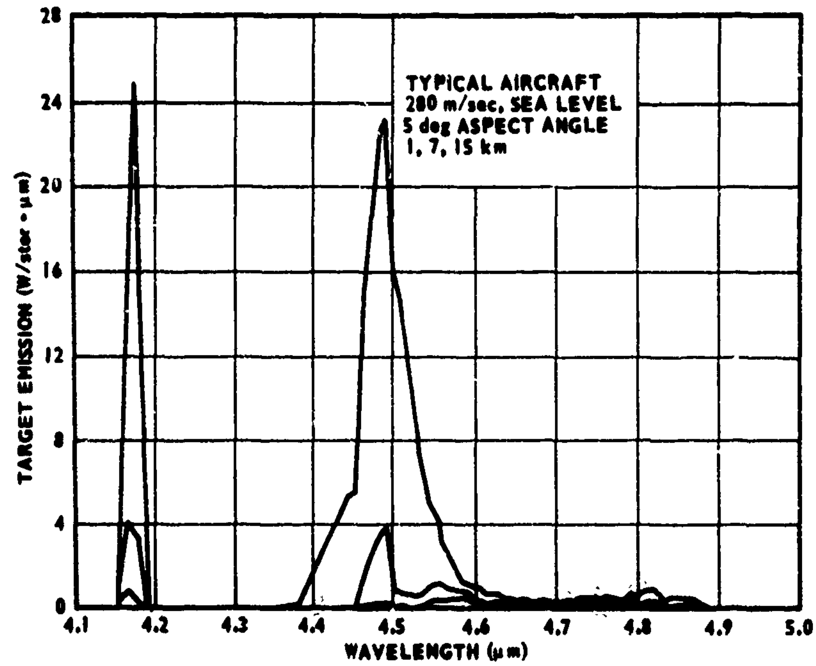

FIGURE 16. REMOTE PLUME SPECTRAL SIGNATURE

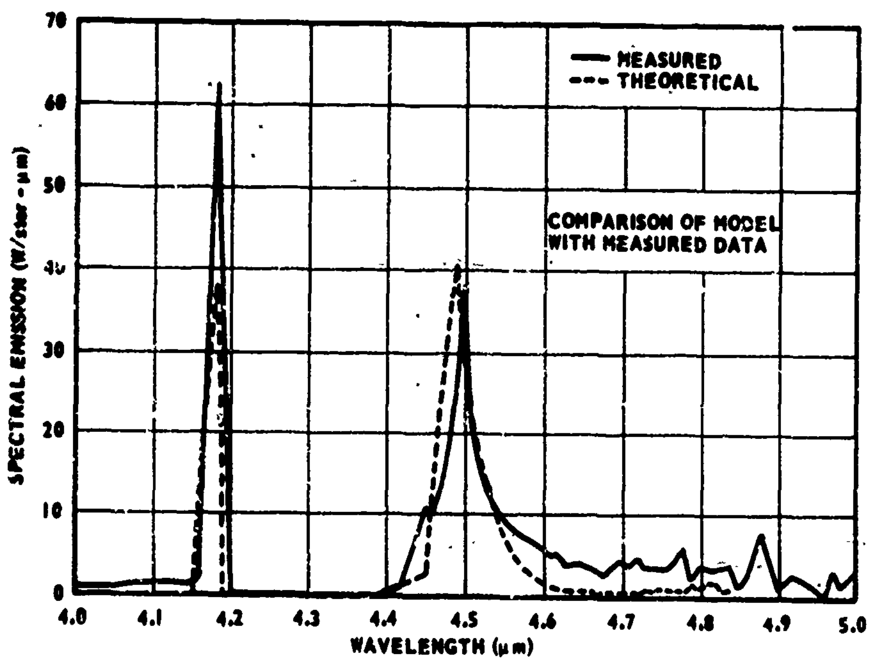

FIGURE 17. COMPARISON OF MODEL WITH EXPERIMENTAL DATA

Section V. RADIATION COMPUTER PROGRAM

A copy of the computer program is shown in Table III. A typical set of input data is shown in Table IV. The first 72 data cards are standard input for each run. These cards alternately list the molecular CO_2 band parameters S/d and $S^{1/2}/d$ as a function of wave number and temperature. The first data record on each card gives the wave number and the remaining seven records list the band parameter at the given wave number as a function of temperature in increments of 300°K (for second data record, T = 300°K; for third, T = 600°K; for eighth, T = 2100°K).

The next two data cards are also standard input for each run and simply contain headings (RADIATION) for the output data headings.

The next two cards are used to document the date of the run and the description or title of the run. The first card contains the date (first 12 columns) and the second the title or name of the run (first 72 columns). The next card must contain two pieces of information according to the format (2I5). The first is the number of X-stations (NXS) that are desired in the calculations and the second is the number of radial or Z points (NZPEX) desired at each X station. (These numbers must be less than or equal to 60 and 8, respectively). The computer checks to insure that these limits are maintained. The coordinate X measures downstream position in centimeters, and Z is the coordinate normal to X, also measured in centimeters. The actual magnitude of these numbers and their spacing is determined by the flow field computation Again NXS and NZPEX count only the number of the points at which calculations are made. The set of flow field data is next read into the computer. This is denoted between statements 172 and 110 of the program listing. An axisymmetric coordinate system is used so that any plume property is defined by the coordinates X and R. Data from the flow field calculations are written on tape at specific X or downstream locations. The number of radial points at each X position is denoted (NRP) and each radial point defined by R(I). At each downstream position where a radiation calculation is desired, the temperature T(I, J) (I denotes the number of the downstream position, J denotes the number of the radial position) in degrees Kelvin, the radial position R(I, J) in centimeters, and the partial pressure of CO_2 (PCO_2) in atmosphere is written on tape. The number of radial points at any given X position must be less than or equal to 25. It is assumed that the total pressure anywhere in the plume is 1 atmosphere. These quantities are not written or read according to a format but rather in binary notation.

Finally a card is read which contains two quantities, ALPHA and ISTOP according to the format (F10.5, I5); ALPHA is the aspect angle in degrees and ISTOP is either 1, 2 or 3. A (1) will terminate the run after the calculations

TABLE III. RADIATION COMPUTER PROGRAM

```
                                                                03/11/70
         TEST        -  EFN    SOURCE STATEMENT  -  IFN(S)  -

C      TRACY JACKSON 7/24/68
C      CO2 4.3 MICRON BAND PLUME SPECTRAL RADIATION PROGRAM
       DIMENSION X(60),R(60,25),T(60,25),PCO2(60,25),SOD(36,7),SOD2(36,7)
       DIMENSION WAVNO(36),WAVLH(36),TT(7),TSPRAD(36)
C
C      READ BAND PARAMETERS FOR CO2 EMISSIVITY CALCULATIONS
C
       REWIND 10                                                          1
       DO 100 I=1,36
       READ(5,1000) WAVNO(I),(SOD(I,J),J=1,7)                             4
       READ(5,1000) WAVNO(I),(SOD2(I,J),J=1,7)                           10
  100  WAVLH(I)=10000./WAVNO(I)
 1000  FORMAT(F7.1,7E9.2)
       DO 101 J=1,7
       TJ=J
       TT(J)=300.*TJ
       DO 101 I=1,36
  101  SOD2(I,J)=SOD2(I,J)*SOD2(I,J)
       DIMENSION DATE(2),TITLE(12),HEADNG(18)
       READ(5,1051)(HEADNG(J),J=1,18)                                    33
 1051  FORMAT(12A6/6A6)
       READ(5,1050) DATE(1),DATE(2),(TITLE(J),J=1,12)                    40
 1050  FORMAT(2A6/12A6)
       WRITE(6,1100) DATE(1),DATE(2),(TITLE(I),I=1,12)                   47
 1100  FORMAT(1H1,40X,52HCO2 4.3 MICRON BAND PLUME SPECTRAL RADIATION PRO
      1GRAM/1H0,62X,2A6/1H0,30X,12A6)
       WRITE(6,1101)                                                     54
 1101  FORMAT(1H0,41HALL PLUME COORDINATES ARE MEASURED IN CM.)
       WRITE(6,1102)                                                     55
 1102  FORMAT(1H0,17HWAVENUMBER-(1/CM))
       WRITE(6,1103)                                                     56
 1103  FORMAT(1H0,20HWAVELENGTH-(MICRONS))
       WRITE(6,1104)                                                     57
 1104  FORMAT(1H0,41HRADIATION-(WATTS/SQ.CM.-MICRON-STERADIAN))
C
C      NXS=NUMBER X STATIONS
C      NZPEX=NUMBER Z POINTS AT EACH X STATION
C
       READ(5,1001) NXS,NZPEX                                            58
 1001  FORMAT(2I5)
       IF(NXS.GT.60) GO TO 170
       IF(NZPEX.GT.8) GO TO 171
       GO TO 172
  170  WRITE(6,1120)                                                     68
 1120  FORMAT(1H1,40H NUMBER OF X-STATIONS MUST BE 60 OR LESS)
       STOP
  171  WRITE(6,1121)                                                     69
 1121  FORMAT(1H1,36HNUMBER OF Z-POINTS MUST BE 8 OR LESS)
       STOP
C
C      READ INPUT DATA TAPE FROM PLUME FLOW FIELD PROGRAM
C      NRP=NUMBER OF RADIAL POINTS
C
  172  CONTINUE
       READ(10) (TITLE(I),I=1,12)                                        70
       READ(10) NORUN                                                    77
       DO 102 I=1,NXS
       READ(10) X(I),NRP                                                 81
       READ(10)(T(I,J),R(I,J),PCO2(I,J),J=1,NRP)                         84
       IF(NRP.LT.25) GO TO 110
       GO TO 102
  110  NRP1=NRP+1
       DO 111 KK=NRP1,25
```

TABLE III. RADIATION COMPUTER PROGRAM (Continued)

```
TEST          - EFN   SOURCE STATEMENT  -  IFN(S)  -

      R(I,KK)=R(I,NRP)
      T(I,KK)=T(I,NRP)
  111 PCO2(I,KK)=PCO2(I,NRP)
  102 CONTINUE
      IPAGE=0
C
C     ALPHA=ASPECT ANGLE IN DEGREES(0 DEG=NOSE-ON)
C     ISTOP=1,WILL TERMINATE PROGRAM AFTER SINGLE ALPHA CALCULATION
C     ISTOP=2,RETURNS TO THIS POINT FOR ANOTHER ALPHA
C     ISTOP=3,RETURNS TO STMT 173 TO READ NEW SET FLOW FIELD DATA
C
  103 READ(5,1010)ALPHA,ISTOP                                        110
 1010 FORMAT(F10.5,I5)
      ALP=ALPHA/57.295780
      CO=COS(ALP)                                                    112
      SO=SIN(ALP)                                                    113
      PI=3.1415926
      DO 160 L=1,36
  160 TSPRAD(L)=0.
      NXSM1=NXS-1
      IF(ALPHA.EQ.0.0.OR.ALPHA.EQ.180.0) NXSM1=1
      DO 106 I=1,NXSM1
      IXO=I
      RO=R(IXO,25)
      XO=X(IXO)+.01
      IF(ALPHA.EQ.180.0) XO=X(NXS)
      ZPEX=NZPEX
      DELZ=RO/ZPEX
      DO 602 M=1,NZPEX
      ZM=M
      ZO=DELZ*(ZM-1.)
      IF(ALPHA.EQ.0.0) RO=2.*R(1,25)+(ZM-1.)*(R(NXS,25)-2.*R(1,25))/ZPEX
      IF(ALPHA.EQ.180.0) RO=(ZM-1.)*(R(NXS,25))/ ZPEX
C
C**************************************************************************
C     CALCULATE COORDINATES X,R ALONG LINE-OF-SIGHT AS FUNCTION OF ITS
C     LENGTH
C
      DIMENSION CR(100),CX(100),CL(100)
      DELL=10.
      IF(ALPHA.EQ.0.0.OR.ALPHA.EQ.180.0) DELL=X(NXS)/98.
  200 XL=0.
      DO 203 J=1,100
      N=J
      APR=XL*SO-SQRT(RO*RO-ZO*ZO)                                    148
      CR(N)=SQRT(ZO*ZO+APR*APR)                                      149
      CX(N)=XO+XL*CO
      CL(N)=XL
      IF(CX(N).LT.0.) GO TO 204
      IF(CX(N).GT.X(NXS)) GO TO 204
      IF(ALPHA.EQ.0.0.OR.ALPHA.EQ.180.0) GO TO 203
      DO 201 K=1,NXS
      KI=K
      IF(CX(N).LE.X(K)) GO TO 202
  201 CONTINUE
  202 IF(CR(N).GT.R(KI,25)) GO TO 204
  203 XL=XL+DELL
C
C     DELL TOO SMALL,INCREASE AS FOLLOWS
C
      DELL=DELL+DELL/2.
      GO TO 200
  204 IF(N.LT.50) GO TO 205
      GO TO 299
```

```
                                                                  03/11/70
           TEST        - EFN    SOURCE STATEMENT  -  IFN(S)  -

C
C     DELL TOO LARGE,DECREASE AS FOLLOWS
C
  205 DELL=CL(N)/75.
C
C     PLUME THICKNESS NEGLIGIBLE AT THIS POINT,MOVE ON TO NEXT POINT
C     AFTER SETTING ALL SPECTRAL RADIATION VALUES EQUAL TO ZERO
C
      IF(DELL.LE.0.005) GO TO 610
      GO TO 299
C
C*********************************************************************
C     CALCULATE PRESSURE AND TEMPERATURE ALONG LINE-OF-SIGHT AT EACH X,R
C
      DIMENSION CT(100),CP(100)
  299 DO 300 J=1,N
      DO 301 L=1,NXS
      NN=L
      IF(CX(J).LE.X(L)) GO TO 302
  301 CONTINUE
  302 DO 303 L=1,25
      MM=L
      IF(CR(J).LE.R(NN,L)) GO TO 304
  303 CONTINUE
  304 DR1=CR(J)-R(NN-1,MM-1)
      DR2=R(NN-1,MM)-R(NN-1,MM-1)
      DR3=CR(J)-R(NN,MM-1)
      DR4=R(NN,MM)-R(NN,MM-1)
      DX1=CX(J)-X(NN-1)
      DX2=X(NN)-X(NN-1)
      TX1=T(NN-1,MM-1)+(T(NN-1,MM)-T(NN-1,MM-1))*DR1/DR2
      TX2=T(NN,MM-1)+(T(NN,MM)-T(NN,MM-1))*DR3/DR4
      CT(J)=TX1+(TX2-TX1)*DX1/DX2
      PX1=PCO2(NN-1,MM-1)+(PCO2(NN-1,MM)-PCO2(NN-1,MM-1))*DR1/DR2
      PX2=PCO2(NN,MM-1)+(PCO2(NN,MM)-PCO2(NN,MM-1))*DR3/DR4
      CP(J)=PX1+(PX2-PX1)*DX1/DX2
      IF(CT(J).LT.300.) CT(J)=300.
  300 IF(CP(J).LT.0.00033) CP(J)=0.00033
C
C*********************************************************************
C     CALCULATE AT EACH SPECTRAL POINT CONSIDERED THE BAND PARAMETERS
C     AT EACH X,R ALONG LINE-OF-SIGHT
C
      DIMENSION CSOD(36,100),CSOD2(36,100)
      DO 401 K=1,N
      IRT=CT(K)/300.
      IF(IRT.LT.1) IRT=1
      DT1=(CT(K)-TT(IRT))/300.
      DO 401 L=1,36
      CSOD(L,K)=SOD(L,IRT)+DT1*(SOD(L,IRT+1)-SOD(L,IRT))
  401 CSOD2(L,K)=SOD2(L,IRT)+DT1*(SOD2(L,IRT+1)-SOD2(L,IRT))
C
C*********************************************************************
C     CALCULATE TRANSMISSION AT EACH SPECTRAL POINT FROM EDGE OF PLUME
C     TO X,R ALONG LINE-OF-SIGHT
C
      DIMENSION Y(100),TRNS(36,100)
      Y(1)=0.
      DO 501 K=2,N
  501 Y(K)=Y(K-1)+0.5*(CL(K)-CL(K-1))*(CP(K)+CP(K-1))
      DO 502 K=1,36
      TRNS(K,1)=1.0
      P=0.
      Q=0.
```

TABLE III. RADIATION COMPUTER PROGRAM (Continued)

```
      TEST          - EFN   SOURCE STATEMENT  -  IFN(S)  -             03/11/70

      DO 502 J=2,N
      DY=0.5*(Y(J)-Y(J-1))
      PVT=0.5*(CT(J)+CT(J-1))
      GAM=0.075*SQRT(300./PVT)                                          294
      P=P+DY*(CSCO(K,J-1)+CSCO(K,J))
      Q=Q+DY*GAM*(CSCO2(K,J-1)+CSCO2(K,J))
      ARG=-2.*(Q/P)*(-1.+SQRT(1.+P*P/Q))                                295
  502 TRNS(K,J)=EXP(ARG)
C
C*****************************************************************
C     CALCULATE TOTAL SPECTRAL EMISSION/UNIT-AREA FROM THE POINT
C     X0,R0,Z0 IN THE DIRECTION OF ALPHA
C                                                                       301
      DIMENSION SPRAD(36,11),ZB(9),NSTEPS(9),DELTAL(9)
      INDEX=0
      GO TO 620
  610 INDEX=100
  620 ZB(M)=Z0
      IF(ALPHA.EQ.0.0.OR.ALPHA.EQ.180.0) ZB(M)=R0
      NSTEPS(M)=N
      DELTAL(M)=DELL
      MX=M
      DO 600 K=1,36
  600 SPRAD(K,M)=0.
      IF(INDEX.GT.50) GO TO 602
      NM1=N-1
      DO 601 K=1,NM1
      PVT=(CT(K)+CT(K+1))*0.5
      XX=14388./PVT
      DO 601 L=1,36
      EMSVTY=(TRNS(L,K)-TRNS(L,K+1))/TRNS(L,K)
      PWL=WAVLH(L)
      PLKRAD=11906.*(PWL**(-5))/(EXP(XX/PWL)-1.)                        334   335
      SPRAD(L,M)=PLKRAD*EMSVTY*TRNS(L,K)+SPRAD(L,M)
  601 CONTINUE
  602 CONTINUE
C
C*****************************************************************
C     PERFORM SPATIAL INTEGRATION OVER PLUME SURFACE TO OBTAIN THE TOTAL
C     SPECTRAL EMISSION IN THE DIRECTION OF ALPHA,ALSO PERFORM AN
C     INTEGRATION OVER THE SPECTRAL REGION TO OBTAIN THE TOTAL RADIATION
C     THAT IS EMITTED FROM THE PLUME AT ASPECT ANGLE ALPHA
C
      MXP1=MX+1
      ZB(MX+1)=R(IXC,25)
      DO 700 L=1,36
      SPRAD(L,MX+1)=0.
  700 SPRAD(L,MX+3)=0.
      IF(ALPHA.EQ.0.0.OR.ALPHA.EQ.180.0) ZB(MX+1)=R(NXS,25)
      DO 701 L=1,36
      DO 701 M=2,MXP1
  701 SPRAD(L,MX+3)=SPRAD(L,MX+3)+(ZB(M)-ZB(M-1))*(SPRAD(L,M-1)+SPRAD(L,
     1M))
      IF(ALPHA.EQ.0.0.OR.ALPHA.EQ.180.0) GO TO 705
      IF(IX0.EQ.1) GO TO 703
      DO 702 L=1,36
  702 TSPRAD(L)=TSPRAD(L)+(X(I)-X(I-1))*(SC/2.)*(SPRAD(L,MX+2)+SPRAD(L,M
     1X+3))
  703 DO 704 L=1,36
  704 SPRAD(L,MX+2)=SPRAD(L,MX+3)
      GO TO 707
  705 DO 706 L=1,36
      DO 706 M=2,MXP1
  706 TSPRAD(L)=TSPRAD(L)+(ZB(M)*ZB(M)-ZB(M-1)*ZB(M-1))*PI*(SPRAD(L,M)+S
```

TABLE III. RADIATION COMPUTER PROGRAM (Concluded)

```
                                                           03/11/70
      TEST          -  EFN   SOURCE STATEMENT   -  IFN(S)  -

     1PRAD(L,M-1))/2.
  707 DO 708 L=1,36
  708 SPRAD(L,MXP1)=SPRAD(L,MX+3)
C
C***********************************************************************
C      WRITE DESIRED OUTPUT
C
      IPAGE=IPAGE+1
      WRITE(6,1200) DATE(1),DATE(2),IPAGE                               417
 1200 FORMAT(1H1,62X,2A6,30X,4HPAGE,13)
      WRITE(6,1201)(TITLE(J),J=1,12)                                    418
      WRITE(6,1285) NCRUN                                               423
 1285 FORMAT(1H0,60X,7HRUN NO=,I4)
 1201 FORMAT(1H0,30X,12A6)
      ABXX=NSTEPS(1)-1
      ROT2=ABXX*DELTAL(1)
      WRITE(6,1202) ALPHA,X0,ROT2                                       424
 1202 FORMAT(1H0,14H ASPECT ANGLE=,E10.4,5X,20HDOWNSTREAM POSITION=,E10.
     14,5X,16HPLUME THICKNESS=,F10.4)
      WRITE(6,1500)(NSTEPS(J),J=1,MX)                                   425
 1500 FORMAT(1H0,7H STEPS=,6X,9I12)
      WRITE(6,1501)(DELTAL(J),J=1,MX)                                   430
 1501 FORMAT(1H ,9H DELTA L=,7X,9E12.4)
      WRITE(6,1203)(ZB(J),J=1,MX)                                       435
 1203 FORMAT(1H ,17H RADIAL POSITION=,E11.4,8E12.4)
      MX2=2*MXP1
      WRITE(6,1204)(HEADNG(J),J=1,MX2)                                  440
 1204 FORMAT(1H0,17H WAVNMBR   WAVLNGH,2X,18A6)
      DO 1205 J=1,36
 1205 WRITE(6,1206) WAVNC(J),WAVLH(J),(SPRAD(J,K),K=1,MXP1)             447
 1206 FORMAT(1H ,F7.0,F9.3,9E12.4)
      DIMENSION RUNITL(60)
      RUNITL(1)=0.
      DO 1250 J=2,36
 1250 RUNITL(1)=RUNITL(1)+(WAVLH(J-1)-WAVLH(J))*0.5*(SPRAD(J-1,MXP1)+
     1SPRAD(J,MXP1))
      WRITE(6,1251) RUNITL(1)                                           465
 1251 FORMAT(1H0,46HRADIATION/UNIT LENGTH OF PLUME(WATTS/STER-CM)=,E11.4
     1)
      WRITE(6,1207)                                                     467
 1207 FORMAT(1H0,20X,94HNOTE-THE LAST RADIATION COLUMN ABOVE GIVES THE S
     1PECTRAL RADIATION/UNIT LENGTH OF PLUME SURFACE)
  106 CONTINUE
      IPAGE=IPAGE+1
      WRITE(6,1200) DATE(1),DATE(2),IPAGE                               471
      WRITE(6,1201)(TITLE(J),J=1,12)                                    472
      WRITE(6,1208) ALPHA                                               479
 1208 FORMAT(1H0,14H ASPECT ANGLE=,F10.4)
      TOTRAD=0.
      DO 709 L=2,36
  709 TOTRAD=TOTRAD+(WAVLH(L-1)-WAVLH(L))*(TSPRAD(L-1)+(TSPRAD(L)))
      TOTRAD=TOTRAD/2.
      WRITE(6,1209)                                                     490
 1209 FORMAT(1H0,37H WAVNMBR   WAVLNGH   SPECTRAL RADIATION)
      WRITE(6,1210)(WAVNO(J),WAVLH(J),TSPRAD(J),J=1,36)                 491
 1210 FORMAT(1H ,F7.0,F9.3,4X,E12.4)
      WRITE(6,1211) TOTRAD                                              500
      CENTR=0.
      DO 1252 I=1,NXSM1
 1252 RUNITL(I)=RUNITL(I)*X(I)*SC*SC
      DO 1253 I=2,NXSM1
 1253 CENTR=CENTR+(X(I)-X(I-1))*0.5*(RUNITL(I-1)+RUNITL(I))
      CENTR=CENTR/TOTRAD
      WRITE(6,1254) CENTR                                               520
 1254 FORMAT(1H0,9HCENTROID=,E11.4)
 1211 FORMAT(1H0,24HTOTAL RADIATION EMITTED=,E10.4,11H WATTS/STER)
      GO TO(107,103,172),ISTOP
  107 REWIND 10                                                         522
      STOP
      END
```

TABLE IV. TYPICAL SET INPUT DATA

```
$DATA
 2050.  2.60E-03 4.80E-04 3.40E-04 4.10E-04 8.20E-04 5.70E-03 2.60E-02
 2050.  4.60E-02 6.60E-02 1.33E-01 3.35E-01 7.90E-01 2.90E-00 8.90E-00
 2060.  8.01E-03 1.03E-03 5.72E-04 6.37E-04 1.37E-03 9.08E-03 3.56E-02
 2060.  5.25E-02 7.50E-02 1.49E-01 [illegible].76E-01 1.00E-00 3.60E-00 1.00E+01
 2070.  1.87E-02 1.89E-03 9.57E-04 1.06E-03 2.28E-03 1.42E-02 4.76E-02
 2070.  6.00E-02 8.42E-02 1.68E-01 4.10E-01 1.28E-00 4.40E-00 1.13E+01
 2080.  1.[illegible]5E-02 1.94E-03 1.30E-03 1.66E-03 3.81E-03 2.13E-02 6.28E-02
 2080.  6.67E-02 9.25E-02 1.84E-01 4.56E-01 1.63E-00 5.23E-00 1.25E+01
 2090.  6.31E-03 1.63E-03 1.57E-03 2.54E-03 6.41E-03 3.08E-02 8.30E-02
 2090.  7.42E-02 1.19E-01 2.56E-01 5.09E-01 2.06E-00 6.10E-00 1.37E+01
 2100.  1.81E-03 1.47E-03 2.10E-03 2.65E-03 1.06E-02 4.28E-02 1.08E-01
 2100.  7.89E-02 1.67E-01 3.95E-01 6.00E-01 2.54E-00 7.00E-00 1.47E+01
 2110.  9.55E-04 1.26E-03 2.32E-03 1.59E-03 1.73E-02 5.86E-02 1.41E-01
 2110.  8.13E-02 2.01E-01 5.00E-01 7.60E-01 3.04E-00 7.90E-00 1.57E+01
 2120.  5.65E-04 8.82E-04 1.70E-03 2.46E-03 2.80E-02 8.05E-02 1.81E-01
 2120.  8.40E-02 2.19E-01 5.58E-01 9.73E-01 3.59E-00 8.76E-00 1.66E+01
 2130.  4.88E-04 6.96E-04 1.78E-03 4.98E-03 4.38E-02 1.15E-01 2.31E-01
 2130.  8.68E-02 2.35E-01 6.12E-01 1.24E-00 4.19E-00 9.60E-00 1.75E+01
 2140.  4.78E-04 7.30E-04 1.73E-03 9.59E-03 6.73E-02 1.63E-01 2.95E-01
 2140.  8.97E-02 2.50E-01 6.66E-01 1.60E-00 4.85E-00 1.04E+01 1.82E+01
 2150.  4.91E-04 7.81E-04 2.20E-03 1.82E-02 1.01E-01 2.25E-01 3.73E-01
 2150.  9.24E-02 2.66E-01 7.40E-01 2.01E-00 5.63E-00 1.12E+01 1.90E+01
 2160.  5.22E-04 8.56E-04 7.78E-03 5.4[illegible]E-02 1.53E-01 3.06E-01 4.68E-01
 2160.  9.60E-02 2.95E-01 8.77E-01 2.51E-00 6.48E-00 1.20E+01 1.98E+01
 2170.  5.81E-04 1.01E-03 4.03E-03 8.16E-02 2.28E-01 4.07E-01 5.80E-01
 2170.  9.87E-02 3.55E-01 1.11E-00 3.15E-00 7.35E-00 1.36E+01 2.03E+01
 2180.  6.95E-04 1.46E-03 8.82E-03 1.09E-01 3.32E-01 5.36E-01 7.10E-01
 2180.  1.02E-01 4.22E-01 1.44E-00 3.91E-00 8.26E-00 1.39E+01 2.05E+01
 2190.  9.01E-04 2.60E-03 2.18E-02 1.88E-01 4.70E-01 7.00E-01 8.57E-01
 2190.  1.12E-01 4.90E-01 1.72E-00 4.81E-00 9.27E-00 1.47E+01 2.06E+01
 2200.  1.28E-03 6.27E-03 5.06E-02 3.15E-01 6.56E-01 8.83E-01 1.00E-00
 2200.  1.29E-01 5.81E-01 2.10E-00 5.81E-00 1.05E+01 1.56E+01 2.10E+01
 2210.  2.45E-03 1.65E-02 1.00E-01 4.92E-01 8.88E-01 1.11E-00 1.17E-00
 2210.  1.32E-01 6.97E-01 2.57E-00 6.90E-00 1.19E+01 1.64E+01 2.17E+01
 2220.  7.95E-03 4.54E-02 2.02E-01 7.28E-01 1.16E-00 1.35E-00 1.36E-00
 2220.  1.37E-01 8.40E-01 3.02E-00 8.02E-00 1.33E+01 1.72E+01 2.25E+01
 2230.  3.10E-02 1.22E-01 3.67E-01 1.04E-00 1.46E-00 1.61E-00 1.55E-00
 2230.  2.65E-02 1.08E-00 3.65E-00 9.12E-00 1.45E+01 1.81E+01 2.35E+01
 2240.  [illegible].84E-02 2.66E-01 6.95E-01 1.46E-00 1.8[illegible]E-00 1.86E-00 1.72E-00
 2240.  [illegible].32E-01 1.48E-00 4.43E-00 1.01E+01 1.55E+01 1.89E+01 2.41E+01
 2250.  2.32E-01 [illegible].86E-01 5.[illegible]3E-01 1.98E-00 2.22E-00 2.11E-00 1.87E-00
 2250.  6.[illegible]E-02 2.04E-00 5.25E-00 1.11E+01 1.59E+01 1.89E+01 2.33E+01
 2260.  3.22E-01 7.93E-01 1.53E-00 2.69E-00 2.61E-00 2.32E-00 1.98E-00
 2260.  1.01E-00 2.65E-00 5.99E-00 1.18E+01 1.59E+01 1.85E+01 2.17E+01
 2270.  5.2[illegible]E-01 1.26E-00 2.36E-00 3.27E-00 2.96E-00 2.49E-00 2.06E-00
 2270.  1.18E-00 3.20E-00 [illegible].53E-00 1.24E+01 1.57E+01 1.78E+01 1.96E+01
 2280.  7.99E-01 2.20E-00 3.52E-00 3.94E-00 3.26E-00 2.61E-00 2.10E-00
 2280.  1.81E-00 3.79E-00 3.96E-00 1.27E+01 1.52E+01 1.57E+01 1.74E+01
 2290.  1.84E-00 4.3[illegible]E-00 5.10E-00 4.53E-00 3.48E-00 2.69E-00 2.12E-00
 2290.  2.57E-00 4.37E-00 7.80E-00 1.28E+01 1.48E+01 1.58E+01 1.59E+01
 2300.  4.40E-00 7.42E-00 6.77E-00 4.95E-00 3.60E-00 2.71E-00 2.11E-00
 2300.  4.01E-00 5.38E-00 8.90E-00 1.27E+01 1.42E+01 1.47E+01 1.45E+01
 2310.  8.72E-00 1.12E+01 7.90E-00 5.14E-00 3.63E-00 2.69E-00 2.07E-00
 2310.  6.26E-00 7.39E-00 1.02E+01 1.23E+01 1.32E+01 1.34E+01 1.30E+01
 2320.  1.34E+01 1.46E+01 8.25E-00 5.14E-00 3.60E-00 2.65E-00 2.01E-00
 2320.  9.31E-00 1.40E+01 1.12E+01 1.16E+01 1.22E+01 1.21E+01 1.15E+01
 2330.  1.67E+01 1.4[illegible]E+01 7.97E-00 5.08E-00 3.57E-00 2.61E-00 1.95E-00
 2330.  1.22E+01 1.14E+01 1.12E+01 1.08E+01 1.10E+01 1.07E+01 1.00E+01
 2340.  1.76E+01 1.11E+01 7.45E-00 5.10E-00 3.35E-00 2.53E-00 1.25E-00
 2340.  1.44E+01 1.10E+01 1.04E+01 [illegible].65E-00 5.70E-00 9.22E-00 8.52E-00
 2350.  1.73E+01 [illegible]E+01 7.67E-00 5.27E-00 3.50E-00 2.40E-00 1.59E-00
 2350.  1.59E+01 [illegible]E+01 [illegible].50E-00 8.51E-00 8.15E-00 7.61E-00 7.22E-00
 2360.  1.79E+01 1.56E+01 1.00E+01 5.33E-00 3.28E-00 2.12E-00 1.43E-00
 2360.  1.80E+01 [illegible]E+01 7.60E-00 6.57E-00 6.33E-00 5.77E-00 5.45E-00
 2370.  2.[illegible]E+01 1.80E+01 7.50E-00 4.90E-00 2.69E-00 1.67E-00 1.09E-00
 2370.  6.97E-00 [illegible].4[illegible]E-00 5.90E-[illegible] [illegible].50E-00 4.56E-00 4.12E-00 3.67E-00
 2380.  1.51E+01 7.20E-00 [illegible].00E-00 3.07E-00 1.77E-00 1.05E-00 6.50E-01
 2380.  2.65E-00 3.[illegible]E-00 4.10E-00 2.80E-00 2.30E-00 1.90E-00 1.60E-00
 2390.  2.97E-01 9.47E-0[illegible] 1.70E-00 1.20E-00 7.20E-01 4.80E-01 3.00E-01
 2390.  7.4[illegible]E-01 1.40E+[illegible] 1.90E-00 1.49E-00 1.20E-00 1.00E-00 9.00E-01
 2400.  5.01E-02 7.5[illegible]E-02 1.06E-01 1.50E-01 1.50E-01 1.30E-01 1.00E-01
 2400.  4.03E-01 [illegible].1[illegible]E-01 6.65E-01 [illegible].00E-01 8.60E-01 8.10E-01 8.00E-01
RADIATION  RADIATION  RADIATION  RADIATION  RADIATION  RADIATION
RADIATION  RADIATION  RADIATION
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   50     7
  99.
```

are finished for a particular ALPHA, a (2) will return the program to accept a new ALPHA and ISTOP, and a (3) returns the program to read a new set of flow field data. The input data sequence is summarized in Table V.

TABLE V. INPUT DATA SEQUENCE

Card No.	Column No.	Description	Format
1-72	1-7	* Wavenumber	F7.1
1-72/odd	8-70	* 7-S/d values (300, 600, . . . , 2100 °K)	7E9.2
1-72/even	8-70	* 7-$S^{1/2}$/d values (300, 600, . . . , 2100 °K)	7E9.2
73-74	1-72	* Printout headings (RADIATION)	12A6/4A6
75	1-12	Date	2A6
76	1-72	Title	12A6
77	1-5	Number X Stations	I5
	6-10	Number Z points each X	I5
78	1-10	Aspect Angle	F10.5
	11-15	ISTOP	15

* Standard for all runs.

A typical set of output data from the program is shown in Table VI. The aspect angle is listed in degrees, the downstream position is given in centimeters, and the plume thickness at the downstream position (X) is also given in centimeters. At each downstream position, the thickness along the line of sight is divided in a number of segments to make the radiation calculations. The number of such segments or zones is denoted by STEPS and the size of each step is indicated by DELTAL in centimeters. These quantities are automatically calculated by the computer. The Z coordinate, previously described, gives the radial position at which the calculation is being made at a particular downstream location. This RADIAL POSITION is also given in centimeters.

The first two tabulated columns of data give the wave number (cm^{-1}) and wavelength (μ). Next N radiation columns are listed, of which the first N-1 gives the radiation emitted from the plume surface in the direction of at the downstream location (X) and radial position (Z). This is given in watts per steradian-micrometer-cm^2. The last radiation column for which no radial position is indicated gives the spectral radiation per unit length of plume surface, i.e., the first N-1

TABLE VI. TYPICAL OUTPUT DATA

[illegible] 4.3 MICRON BAND PLUME SPECTRAL RADIATION [illegible]

ALL PLUME COORDINATES ARE MEASURED IN CM.

WAVENUMBER=(1/CM)

WAVELENGTH=(MICRONS)

RADIATION=(WATTS/[illegible]-MICRON-STERADIAN)

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TYPICAL TURBOJET AIRCRAFT - SEA LEVEL CONDITIONS - 900 DEG EGT STATIC

RUN NO= 1

ASPECT ANGLE=0.9000E 02   DOWNSTREAM POSITION=0.1236E 03   PLUME THICKNESS=0.1440E 03

STEPS=		73	72	75	76	75	71	73	
DELTA L=		0.2000E 01	0.2000E 01	0.1867E 01	0.1733E 01	0.1600E 01	0.1467E 01	0.1067E 01	
RADIAL POSITION=		0.	0.1003E 02	0.2006E 02	0.3009E 02	0.4013E 02	0.5016E 02	0.6019E 02	
WAVNMBR	WAVLNGH	RADIATION	RADIATION	RADIATION	RADIATION	RADIATION	RADIATION	RADIATION	RADIATION
2050.	4.878	0.1180E-03	0.1110E-03	0.8527E-04	0.2835E-04	0.6209E-05	0.9531E-06	0.1988E-06	0.5837E-02
2060.	4.854	0.2087E-03	0.1974E-03	0.1558E-03	0.6157E-04	0.1767E-04	0.2803E-05	0.5918E-06	0.1084E-01
2070.	4.831	0.3630E-03	0.3445E-03	0.2764E-03	0.1190E-03	0.3802E-04	0.6089E-05	0.1308E-05	0.1940E-01
2080.	4.808	0.4710E-03	0.4443E-03	0.3458E-03	0.1257E-03	0.3466E-04	0.5543E-05	0.1150E-05	0.2392E-01
2090.	4.785	0.5396E-03	0.5053E-03	0.3779E-03	0.1022E-03	0.1567E-04	0.2221E-05	0.44[illegible]1E-06	0.2555E-01
2100.	4.762	0.7045E-03	0.6570E-03	0.4792E-03	0.1017E-03	0.6822E-05	0.7334E-06	0.1322E-06	0.3206E-01
2110.	4.739	0.7748E-03	0.7214E-03	0.5206E-03	0.9848E-04	0.4697E-05	0.4302E-06	0.7127E-07	0.3477E-01
2120.	4.717	0.5711E-03	0.5315E-03	0.3828E-03	0.7076E-04	0.3073E-05	0.2643E-06	0.4210E-07	0.2556E-01
2130.	4.695	0.4665E-03	0.4341E-03	0.3122E-03	0.5697E-04	0.2485E-05	0.2184E-06	0.3524E-07	0.2085E-01
2140.	4.673	0.5853E-03	0.5442E-03	0.3892E-03	0.6645E-04	0.2525E-05	0.2153E-06	0.3407E-07	0.2599E-01
2150.	4.651	0.7455E-03	0.6927E-03	0.4932E-03	0.7962E-04	0.2644E-05	0.2208E-06	0.3444E-07	0.3292E-01
2160.	4.630	0.9446E-03	0.8773E-03	0.6226E-03	0.9590E-04	0.2846E-05	0.2335E-06	0.3559E-07	0.4156E-01
2170.	4.608	0.1371E-02	0.1273E-02	0.8999E-03	0.1310E-03	0.3270E-05	0.2612E-06	0.3952E-07	0.6004E-01
2180.	4.587	0.2788E-02	0.2772E-02	0.1950E-02	0.2601E-03	0.4435E-05	0.3305E-06	0.4758E-07	0.1300E 00
2190.	4.566	0.7304E-02	0.6779E-02	0.4769E-02	0.6065E-03	0.7247E-05	0.4852E-06	0.6358E-07	0.3173E 00
2200.	4.545	0.1633E-01	0.1519E-01	0.1076E-01	0.1396E-02	0.1578E-04	0.9060E-06	0.1018E-06	0.7127E 00
2210.	4.525	0.3104E-01	0.2497E-01	0.2085E-01	0.2898E-02	0.3952E-04	0.2097E-05	0.2124E-06	0.1370E 01
2220.	4.505	0.5583E-01	0.5248E-01	0.3886E-01	0.6073E-02	0.1088E-03	0.5982E-05	0.6350E-06	0.2517E 01
2230.	4.484	0.8418E-01	0.7986E-01	0.6142E-01	0.1146E-01	0.2949E-03	0.1808E-04	0.2152E-05	0.3915E 01
2240.	4.464	0.1083E 00	0.1036E 00	0.8276E-01	0.1836E-01	0.6334E-03	0.4480E-04	0.6008E-05	0.5208E 01
2250.	4.444	0.1250E 00	0.1205E 00	0.9971E-01	0.2569E-01	0.1091E-02	0.8733E-04	0.1279E-04	0.6211E 01
2260.	4.425	0.1314E 00	0.1275E 00	0.1086E 00	0.3200E-01	0.1577E-02	0.1347E-03	0.2042E-04	0.6730E 01
2270.	4.405	0.1291E 00	0.1257E 00	0.1092E 00	0.3639E-01	0.2051E-02	0.1794E-03	0.2680E-04	0.6783E 01
2280.	4.386	0.1173E 00	0.1142E 00	0.1001E 00	0.3706E-01	0.2610E-02	0.2522E-03	0.3857E-04	0.6278E 01
2290.	4.367	0.9648E-01	0.9384E-01	0.8226E-01	0.3289E-01	0.3020E-02	0.3720E-03	0.7022E-04	0.5230E 01
2300.	4.348	0.7374E-01	0.7155E-01	0.6246E-01	0.2630E-01	0.3055E-02	0.4796E-03	0.1160E-03	0.4029E 01
2310.	4.329	0.4995E-01	0.4823E-01	0.4147E-01	0.1820E-01	0.2810E-02	0.5464E-03	0.1627E-03	0.2736E 01
2320.	4.310	0.3166E-01	0.3036E-01	0.2552E-01	0.1152E-01	0.2348E-02	0.5567E-03	0.1964E-03	0.1732E 01
2330.	4.292	0.2417E-01	0.2307E-01	0.1905E-01	0.8543E-02	0.1985E-02	0.5337E-03	0.2112E-03	0.1314E 01
2340.	4.274	0.2360E-01	0.2247E-01	0.1840E-01	0.7920E-02	0.1842E-02	0.5173E-03	0.2139E-03	0.1267E 01
2350.	4.255	0.2248E-01	0.2136E-01	0.1737E-01	0.7404E-02	0.1780E-02	0.5097E-03	0.2121E-03	0.1201E 01
2360.	4.237	0.2510E-01	0.2390E-01	0.1945E-01	0.7851E-02	0.1737E-02	0.4815E-03	0.2021E-03	0.1326E 01
2370.	4.219	0.4144E-01	0.3969E-01	0.3273E-01	0.1279E-01	0.2074E-02	0.4499E-03	0.1651E-03	0.2179E 01
2380.	4.202	0.7963E-01	0.7666E-01	0.6397E-01	0.2203E-01	0.2214E-02	0.3308E-03	0.9109E-04	0.4115E 01
2390.	4.184	0.9377E-01	0.9000E-01	0.7372E-01	0.2143E-01	0.1231E-02	0.9787E-04	0.1273E-04	0.4682E 01
2400.	4.167	0.2877E-01	0.2711E-01	0.2051E-01	0.4486E-02	0.1942E-03	0.1416E-04	0.1972E-05	0.1338E 01

RADIATION/UNIT LENGTH OF PLUME(WATTS/STER-CM)= 0.1358E 01

NOTE-THE LAST RADIATION COLUMN ABOVE GIVES THE SPECTRAL RADIATION/UNIT LENGTH OF PLUME SURFACE

TABLE VI. TYPICAL OUTPUT DATA (Continued)

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TYPICAL TURBOJET AIRCRAFT - SEA LEVEL CONDITIONS - 900 CEG EGT STATIC

RUN NO= 1

ASPECT ANGLE=0.90CCE 02 DOWNSTREAM PCSITICN=0.104CE 04 PLUME THICKNESS=0.75CCE C3

STEPS=		76	76	73	70	64	55	75	
DELTA L=		0.1000E 02	C.1000E C2	0.1000E 02	0.1000E 02	0.1000F 02	0.1000E C2	0.56C0E 01	
RADIAL POSITION=		C.	C.5209E C2	0.1042E 03	C.1563E 03	0.2084E 03	0.26C5E C3	0.3126E C3	
WAVNMBR	WAVLNGH	RADIATION	RADIATICN	RADIATICN	RADIATION	RADIATION	RADIATICN	RADIATICN	RADIATICN
2050.	4.878	C.1092E-04	0.8C85E-C5	0.4052E-C5	C.2075E-05	0.1258E-05	0.8362E-C6	C.5744E-C6	0.2328E-C2
2060.	4.854	C.3017E-04	0.2241E-04	0.1130E-04	C.5835E-05	0.3574E-05	0.2401E-C5	C.1669E-05	0.6489E-02
2070.	4.831	0.5797E-04	0.4276E-C4	0.2146E-04	0.1120E-04	0.7001E-05	0.4815E-C5	0.3439E-C5	0.1247E-01
2080.	4.808	0.5482E-04	0.4042E-C4	0.2021F-04	0.1046E-04	0.6471E-05	0.4404E-C5	C.3111E-C5	0.1172E-01
2090.	4.785	0.2625E-C4	C.19C8E-C4	0.9270E-05	0.4654E-05	0.2800E-05	0.1856E-C5	C.1276E-C5	C.5424E-02
2100.	4.762	C.1025E-04	C.7CC4E-C5	0.3074E-C5	C.1446E-05	0.8434E-06	0.5453E-C6	C.3744E-C6	C.1919E-C2
2110.	4.739	C.6624E-05	C.4357E-C5	C.1784E-C5	C.7993E-06	0.4554E-06	0.2931E-C6	C.195CE-C6	C.1167E-02
2120.	4.717	C.4234E-05	0.2744E-05	0.1091E-05	0.4778E-06	0.2693E-06	0.1723E-C6	C.1168E-C6	0.7280E-03
2130.	4.695	0.3452E-05	0.2249E-C5	0.9031E-06	0.3985E-06	0.2254E-06	0.1445E-C6	0.9797E-C7	0.5985E-03
2140.	4.673	0.3469E-05	0.2243F-C5	0.8881E-06	0.3846E-06	0.2180F-06	0.1393E-C6	C.9439E-C7	0.5944E-03
2150.	4.651	C.3604E-C5	C.2319E-C5	0.9088E-06	0.3934E-06	0.2204E-06	0.1406E-C6	C.9515E-C7	0.6126E-C3
2160.	4.630	C.3855E-C5	0.2470E-C5	0.9597E-06	0.4126E-06	0.2303E-06	0.1466E-C6	C.9921E-C7	C.6508E-03
2170.	4.608	0.4386E-05	0.2793E-C5	0.1071E-05	0.4555E-06	0.2529E-06	0.1606E-C6	C.1085E-C6	0.7329E-03
2180.	4.587	C.5801E-05	0.3634E-C5	0.1346E-05	0.5567E-06	0.3046E-06	0.1919E-C6	C.1254E-C6	C.9442E-03
2190.	4.566	0.9135E-05	C.5580F-C5	0.1954E-05	0.7691E-06	0.4098E-06	0.2545E-C6	C.17C8E-C6	C.1428E-02
2200.	4.545	0.1493E-04	0.1116E-C4	0.3580E-05	C.1291E-05	0.6526E-06	0.3932E-C6	C.2613E-C6	0.2793E-02
2210.	4.525	C.4015E-04	0.2673E-C4	0.8179E-C5	0.2793E-05	0.1362E-05	0.8030E-C6	C.5257E-C6	C.6613E-02
2220.	4.505	C.1263E-03	C.7385E-C4	0.2316E-04	0.8130E-05	0.4042E-05	0.2412E-C5	C.16CCE-C5	0.1837E-01
2230.	4.484	C.3322E-03	C.2000E-03	0.6723E-04	0.2535E-04	0.1321E-04	0.8135E-C5	0.5484E-C5	C.5059E-01
2240.	4.464	0.6547E-03	0.4090E-C3	0.1493E-03	C.6098E-04	0.3356E-04	0.2149E-C4	C.1451E-C4	0.1059E C0
2250.	4.444	C.5958E-03	0.8410E-C3	0.2502E-C3	0.1090E-03	0.6285E-04	0.4177E-C4	C.2952E-C4	C.1701E 00
2260.	4.425	C.1267E-C2	0.8303E-C3	0.3372E-03	C.1527E-03	0.9071E-04	0.6177E-C4	C.4525E-C4	C.2241E C0
2270.	4.405	C.1463E-02	C.9709E-C3	0.4036E-03	0.1865E-03	0.1125E-03	0.7752E-C4	C.5742E-04	0.2647E 00
2280.	4.386	0.1569E-02	0.1068E-02	0.4683E-03	0.2276E-03	0.1424E-03	0.1011E-C3	0.77C0E-C4	0.2989E 00
2290.	4.367	0.1411E-C2	0.1007E-C2	0.4967E-03	0.2734E-03	0.1874E-03	0.1431E-C3	C.116CE-C3	0.3051E C0
2300.	4.348	C.1063E-02	0.8C43E-C3	0.4593E-03	C.2930E-03	0.2223E-03	0.1835E-C3	C.1585E-C3	0.2764E 00
2310.	4.329	C.6860E-03	0.5588E-C3	0.3773E-03	C.2796E-03	0.2332E-03	0.2062E-C3	C.1879E-C3	C.2278E C0
2320.	4.310	C.4239E-03	0.3747E-C3	0.2988E-03	0.2520E-03	0.2266E-03	0.2107E-C3	C.1953E-C3	C.1848E 00
2330.	4.292	0.3150E-03	0.2928E-03	0.2568E-03	0.2320E-03	0.2169E-C3	0.2069E-03	0.1952E-C3	0.1627E 00
2340.	4.274	0.2763E-03	0.2620F-03	0.2383E-03	0.2210E-03	0.2097F-03	0.2020E-C3	C.1957E-C3	C.1528E 00
2350.	4.255	C.2580E-03	0.2469E-C3	0.2282E-03	C.2138E-03	0.2040E-03	0.1972E-C3	C.1916E-C3	C.1470E C0
2360.	4.237	C.2761E-03	0.2586E-C3	0.2307E-03	C.2116E-03	0.1998E-03	0.1920E-C3	C.1857E-C3	C.1476E C0
2370.	4.219	0.4667E-03	0.3912E-C3	0.2845E-03	0.2267E-03	0.1987E-03	0.1822E-03	0.17C7E-C3	C.1758E C0
2380.	4.202	0.9275E-C3	0.6737E-03	0.3574E-C3	C.2184E-03	0.1635E-03	0.1347E-03	0.1167E-C3	0.2217E 00
2390.	4.184	C.9092E-C3	0.5893E-C3	0.2315E-03	C.1007E-03	0.5813E-04	0.3871E-C4	C.2754E-C4	0.1564E 00
2400.	4.167	0.2226E-03	0.1396E-C3	0.5173E-C4	C.2142E-04	0.1181E-04	0.7519E-C5	0.5143E-C5	C.3632E-01

RADIATION/UNIT LENGTH OF PLUME(WATTS/STER-CM)= 0.6334E-01

NOTE-THE LAST RADIATICN COLUMN ABCVE GIVES THE SPECTRAL RADIATION/UNIT LENGTH CF PLUME SURFACE

TABLE VI. TYPICAL OUTPUT DATA (Concluded)

6 MAR 70

TYPICAL TURBOJET AIRCRAFT - SEA LEVEL CONDITIONS - 900 DEG EGT STATIC

ASPECT ANGLE=0.9CCCE C2

WAVNMR	WAVLNGH	SPECTRAL RADIATION
2C50.	4.878	0.3897E 01
2060.	4.854	0.8861E 01
2C70.	4.831	0.1698E 02
2C80.	4.808	0.1784E C2
2C90.	4.785	C.1356E C2
21C0.	4.762	0.1522E 02
2110.	4.739	0.1337E 02
2120.	4.717	0.9694E 01
2130.	4.695	C.7884E C1
2140.	4.674	C.9569E 01
2150.	4.651	0.1187E C2
2160.	4.630	C.1475E 02
2170.	4.608	C.2051E C2
2180.	4.587	0.44C2E 02
2190.	4.566	0.1058E C3
2200.	4.545	0.2381E 03
2210.	4.525	0.4642E 03
2220.	4.505	0.8753E 03
2230.	4.484	0.1422E 04
2240.	4.464	0.1973E 04
2250.	4.444	0.2430E 04
2260.	4.425	C.27C5E 04
2270.	4.405	0.2799E 04
2280.	4.385	0.2674E C4
2290.	4.367	0.2298E 04
2300.	4.348	0.1824E 04
2310.	4.329	0.1317E C4
2320.	4.310	0.9324E 03
2330.	4.292	0.7772E 03
2340.	4.274	C.7651E 03
2350.	4.255	0.7421E 03
2360.	4.237	C.7693E 03
2370.	4.219	0.1069E C4
2380.	4.202	0.1708E 04
2390.	4.184	0.1892E 04
2400.	4.167	0.5212E 03

TOTAL RACIATION EMITTED=C.5777E 03 WATTS/STER

CENTROID= 0.2151F C3

values of radiation have been integrated across the radial position coordinate. The last column therefore has units of watts per steradian-micrometer-cm. The next to the last line of printout gives the radiation per unit length of plume surface; i. e., the last column has been integrated over the spectral regime. As indicated, this has units of watts per steradian-cm.

After the spectral and spatial distributions have been computed for each downstream location at a particular aspect angle, the results are then integrated over the whole surface of the plume. The last output page for a given aspect angle contains this information as a function of both wave number and wavelength This is listed as SPECTRAL RADIATION and given in watts per steradian-micrometer. Next, a spectral integration is performed which gives the total radiation emitted in watts per steradian. Finally the centroid of radiation along the length of the plume is computed and listed in centimeters.

REFERENCES

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6. Baronti, Paolo, Method of Analysis of Mixing Processes with Combustion, Report No. ATL TR No. 106, Advanced Technology Laboratories, Inc., 400 Jericho Turnpike, Jericho, New York, November 1967.

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Appendix
FLOW FIELD PROGRAM

This appendix outlines the flow field frozen mixing computer program which is used to provide the input data to the radiation program. A typical set of input-output data is shown, a description of the input data is given, and the computer program is listed. A brief description of the viscosity options is also included for completeness.

The viscosity option occurs on the second data card and is labelled ITURB by the computer, where ITURB = 0, 1, 2, 3, or 4. The statement ITURB = 0 indicates laminar flow and the viscosity is given by Sutherland's law. For ITURB = 1 or 2, the eddy viscosity is computed from the expressions

$$\mu = K_2 r_{1/2} \rho_0 U_0 \quad , \quad (\mathrm{ITURB} = 1)$$

$$\mu = K_2 r_{1/2} \left| \rho_0 U_0 - \rho_\infty U_\infty \right| \quad , \quad (\mathrm{ITURB} = 2)$$

where K_2, the turbulent viscosity coefficient, is taken to be 0.0285. The subscripts refer to jet center line and ambient conditions, and $r_{1/2}$ is the value of R at $\rho U = 1/2\left(\rho_\infty U_\infty - \rho_0 U_0\right)$. For ITURB = 3, $r_{1/2} = \left| r_{0.99} - r_{0.50} \right|$, where $r_{0.50}$ is the value of R at $U = 1/2\left(U_\infty + U_0\right)$ and $r_{0.99}$ is the value of R at $U = \left(0.01U_\infty + 0.99U_0\right)$. The viscosity is then given by the expression

$$\mu = K_2 r_{1/2} \rho_0 U_0 \quad . \quad (\mathrm{ITURB} = 3)$$

For the option ITURB = 4, the viscosity is computed from the expression

$$\mu = 10^{-4} + X\left(\rho_\infty U_\infty + P_0 U_0\right), \quad (\mathrm{ITURB} = 4)$$

where X is the downstream position. The latter option is utilized for jet aircraft plumes in the core region with this region being defined by the condition $d^2U/dR^2\Big|_{R=0} = 0$. Outside the core model 3 is used for aircraft in flight and model 1 for static conditions. The program automatically selects the mode outlined above when the input data specifies option 4. Table A-I describes the input data sequence for the program. The thermodynamic data are obtained from NASA document SP-3001, pages 308-326. A typical set of input data is shown in Table A-II followed by the program itself in Table A-III. Table A-IV then shows a few pages of selected printout or output generated by the input data described in Table A-I. The initial page specifies the input data; the remaining output gives the properties as a function of downstream and radial position.

The only programmed error message occurs if the summation of the initial specie mass fractions (indicated by SIGMA) differ by more than 1 percent from unity.

The actual output from this program that is used in the radiation model is written on magnetic tape. The program first expands the number of radial points to 25 by defining the plume width to be that radial point where $T/T_{\infty} = 1.05$. This width is then divided into 25 evenly spaced points and the properties determined at each point by interpolation. Dimensions are converted from feet to centimeters, mass fraction to mole fraction or partial pressure, and temperature ratio to absolute temperature. The resulting tape is then read as input to the radiation model.

TABLE A-I. INPUT DATA SEQUENCE

Card No.	Column No.	Description	Format
1	1-72	Title Card	72H
2	1-5	Month (Jan = 01,......, Dec = 12)	I5
	6-10	Day	I5
	11-15	Year (Last Two Digits)	I5
	16-20	Initial number of grid points (if the variable profile option is used) or initial number of points in jet (if the step input option is used).	I5
	21-25	Number of species (21 maximum)	I5
	26-30	Pressure option: 0 = Constant Pressure 1 = Polynomial Fit	I5
	31-35	Viscosity option: 0 = Laminar (Sutherland's Law) 1 = $K_2 r_{1/2}\, \rho_0 U_0$ 2 = $K_2 r_{1/2} \left\| \rho_0 U_0 - \rho_e U_e \right\|$ 3 = $K_2 r_{1/2}\, \rho_0 U_0$ 4 = $10^{-4} + X(\rho_0 U_0 + \rho_e U_e)$	I5
	36-40	Flow option: 0 = Axisymmetric 1 = Two Dimensional	I5

TABLE A-I. INPUT DATA SEQUENCE (Continued)

Card No.	Column No.	Description	Format
	41-45	Input profile option: 0 = Step Input 1 = Variable Profile	I5
3	1-10	First print increment (ft)	E10.8
	11-20	Final X for first print increment (ft)	E10.8
	21-30	Second print increment (ft)	E10.8
	31-40	Final X for second print increment (ft)	E10.8
	41-50	Third print increment (ft)	E10.8
	51-60	Final X for third print increment (ft) and for terminating the case	E10.8
	61-70	X initial (ft)	E10.8
4	1-10	Lewis Number	E10.8
	11-20	Prandtl Number	E10.8
	21-30	The initial radius of the jet in feet if the step input option is used, otherwise $\Delta\Psi$, the radial spacing in streamline coordinates	E10.8
	31-40	K_1 the coefficient of laminar viscosity	E10.8
	41-50	K_2 the coefficient of turbulent viscosity	E10.8
5	1-10	P_0 Pressure fit coefficients:	E10.8
	11-20	P_1 If option 1 is used, P_0 is the pressure in lb/ft^2	E10.8
	21-30	P_2 and P_1, P_2, P_3, P_4 are blank. If option 2 is used, P_i is the	E10.8
	31-40	P_3 coefficient in the pressure polynomial as follows:	E10.8
	41-50	P_4 $P\ (\mathrm{lb/ft^2}) = \sum_{i=0}^{4} p_i X^i$	E10.8
6	-	Thermodynamic data for the different species being considered. There are 3 cards for each specie as described below. The specie may be input in any arbitrary order.	-
6a	1-6	Hollerith representation of the specie (e.g. H20)	A6

TABLE A-I. INPUT DATA SEQUENCE (Continued)

Card No.	Column No.	Description	Format
	11-20	Molecular weight	E10.8
	21-30	T_{1L} lower temperature bound for fit 1	E10.8
	31-40	T_{1H} upper temperature bound for fit 1	E10.8
	41-50	T_{2L} lower temperature bound for fit 2	E10.8
	51-60	T_{2H} upper temperature bound for fit 2	E10.8
6b	1-10	a_1 Coefficients for low	E10.8
	11-20	a_2 temperature fits	E10.8
	21-30	a_3 See NASA SP3001	E10.8
	31-40	a_4	E10.8
	41-50	a_5	E10.8
	51-60	a_6	E10.8
	61-70	a_7	E10.8
6c	1-10	Coefficients for high temperature	E10.8
	11-20	fits	E10.8
	21-30		E10.8
	31-40	NASA SP3001	E10.8
	41-50		E10.8
	51-60		E10.8
	61-70		E10.8
IF THE VARIABLE INPUT OPTION IS USED:			
7	1-10	T_0 Axis value of temperature (°K)	E10.8
	11-20	T_1	E10.8
	11-20	. The values of the temperature	E10.8
	11-20	. at each of the inputted psi	E10.8
	11-20	. grid points are punched	E10.8
	61-70	T_6 7 to a card from the axial value and ending with the free stream values (°K)	E10.8
7'	1-10	T_7	E10.8
		T_7	E10.8

TABLE A-I. INPUT DATA SEQUENCE (Continued)

Card No.	Column No.		Description	Format
		T_7		E10. 8
	61-70	T_{13}		
7"	1-10	T_{14}		E10. 8
		T_{14}		E10. 8
		T_{14}		E10. 8
		T_e	Free stream value of temperature (^0K)	
8	1-10	U_0		E10. 8
	1-10	U_0	The values of the velocity at	E10. 8
			each of the inputted psi grid	E10. 8
			points are punched	
	61-70	U_6	7 to a card from axial value	E10. 8
			and ending with the free stream	
8'	1-10	U_7	values (ft/sec)	E10. 8
	1-10			E10. 8
	1-10			E10. 8
	61-70	U_{13}		
8"	1-10	U_{14}		E10. 8
		U_{14}		E10. 8
		U_{14}		E10. 8
		U_e	Free stream value of velocity	
	IF THE STEP INPUT OPTION IS USED:			
9	1-10	α_1		E10. 8
	11-20	α_2		E10. 8
	21-30	α_3	Axis values of species	E10. 8
	31-40	α_4	mass fractions.	E10. 8
	41-50	α_5		E10. 8
	51-60	α_6		E10. 8
	61-70	α_7		E10. 8
9'	1-10	α_1		E10. 8
	11-20	α_2	Values of species mass fractions	E10. 8
	21-30	α_3	at each inputted psi grid point	E10. 8
	31-40	α_4	are punched on one card per point	E10. 8
	41-50	α_5	beginning with the axial value and	E10. 8
	51-60	α_6	ending with the free stream. A	E10. 8
	61-70	α_7	maximum of 7 species per card.	E10. 8
	61-70	α_7	The order of the species must	

TABLE A-I. INPUT DATA SEQUENCE (Concluded)

Card No.	Column No.	Description		Format
	61-70	α_7	correspond to the order of the	
	61-70	α_7	thermodynamic data (card type 6)	
9"	1-10	α_1	Free stream values	E10.8
	11-20	α_2		E10.8
	21-30	α_3		E10.8
	31-40	α_4		E10.8
	41-50	α_5		E10.8
	51-60	α_6		E10.8
	61-70	α_7		E10.8
IF THE STEP INPUT OPTION IS USED:				
7	1-10	Jet temperature (°K)		E10.8
	11-20	Free stream temperature (°K)		E10.8
	21-30	Jet velocity (ft/sec)		E10.8
	31-40	Free stream velocity (ft/sec)		E10.8
8	1-10	α_1	Specie mass fractions in the jet. A maximum of seven species per card. If there are more than seven species continue on another card in the same format. The order of the species must correspond to the order the thermodynamic data (card type 6) for each specie input.	E10.8
	11-20	α_2		E10.8
	21-30	α_3		E10.8
	31-40	α_4		E10.8
	41-50	α_5		E10.8
	51-60	α_6		E10.8
	61-70	α_7		E10.8
9	1-10	α_1	Specie mass fractions at the edge. Comments for card 8 are applicable.	E10.8
	11-20	α_2		E10.8
	21-30	α_3		E10.8
	31-40	α_4		E10.8
	41-50	α_5		E10.8
	51-60	α_6		E10.8
	61-70	α_7		E10.8
10	1-10	The initial radius of the jet (ft)		E10.8
	11-15	Run number		I5

TABLE A-II. TYPICAL SET OF INPUT DATA

```
$DATA
 TYPICAL TURBOJET AIRCRAFT - SEA LEVEL CONDITIONS - 900 DEG EGT STATIC
   03   06   70   10   4   0   4   0   0
0.25        10.0       1.0        20.0       2.0        50.0       0.0
1.4          .71        1.000      0.0        .0285
2117.
O2          32.0       300.       1000.      1000.      5000.
 3.7189+00-2.5167-03 6.5837-06-8.2999-09 2.7082-12-1.0576+03 3.9081+00
 3.5976+00 7.8146-04-2.2367-07 4.2490-11-3.3460-15-1.1928+03 3.7493+00
N2          28.014     300.       1000.      1000.      5000.
 3.6916+00-1.3333-03 2.6503-06-9.7688-10-9.9772-14-1.0628+03 2.2875+00
 2.8546+00 1.5976-03-6.2566-07 1.1316-10-7.6897-15-8.9017+02 6.3903+00
CO2         44.011     300.       1000.      1000.      5000.
2.1701      1.03781-02-1.0733-056.34591-09-1.6280-12-4.8352+041.06643+01
4.41292+003.19228-03-1.2978-062.41474-10-1.6742-14-4.8944+04-7.2875-01
H2O         18.016     300.       1000.      1000.      5000.
4.15650+00-1.7244-035.69823-06-4.5930-091.42336-12-3.0288+04-6.8616-01
2.67075+003.03171-03-8.5351-071.17908-10-6.1973-15-2.9888+046.88383+00
 900.       300.       1800.         1.
.17535      .75290     .05195     .01980
.2318       .7677      .0005      0.0
  1.000        1
```

TABLE A-III. FLOW FIELD COMPUTER PROGRAM

```
        MAIN1      -  FFN   SOURCE STATEMENT  -  IFN(S)  -                03/09/70

C       MAIN                                                              066S1010
        COMMON R,X,DPDX,POUT,HE,PE,DPOUT,P,DELPSI,CX,XMUT,XMUL,DEL,XMUK1,X
       1MUK2,PRNT,PCNT,UE,RHCE,TE,XP3,RFALF
        COMMON IOUT,MPSI,MHALF,MINIT,IFINIS,NPSI,IPAGE,IPRESS,ISTART,ITURB
       1,ITURA,IJET,NS,MDAY,MONTH,MYEAR,IAX2C,IVAR
        COMMON WTMOLE(21),COEFFP(5),ALPHA(21,59),HCUT(59),RCOTT(59),RT(59)
       1,T(59),H(21,59),RALPHA(21,59),PSI(59),RU(59),U(59),XLE(59),TITLE(1
       22),SUM(59),ETA(59),XMU(59),A(59),AWAIT(59),RHOOUT(59),UOUT(59),TOU
       3T(59),CP(21,59),HSTG(59),RHC(59),Y(59),XMAX(3),XPRT(3),CPBAR(59),S
       4IGMA(59),HBAR(59),AFITS(21,2,7),TFITS(21,4),SPECID(21)
        REWIND 10                                                                1
      1 CALL INPUT                                                               3
        CALL INITAL                                                       066S1033  5
      2 CALL FROZ1                                                               7
        CALL COMPUT                                                              9
        IF(IFINIS.GT.1) GO TO 1
        CALL EXPLIC                                                              1
        IF(IFINIS.GT.1) GO TO 1
        GO TO 2                                                           066S1047
        END                                                               066S1048
                                                                          03/09/70
        FROZ2      -  FFN   SOURCE STATEMENT  -  IFN(S)  -

        SUBROUTINE INPUT                                                  066S0480
        COMMON R,X,DPDX,POUT,HE,PE,DPOUT,P,DELPSI,CX,XMUT,XMUL,DEL,XMUK1,X
       1MUK2,PRNT,PCNT,UE,RHCE,TE,XP3,RFALF
        COMMON IOUT,MPSI,MHALF,MINIT,IFINIS,NPSI,IPAGE,IPRESS,ISTART,ITURB
       1,ITURA,IJET,NS,MDAY,MONTH,MYEAR,IAX2C,IVAR
        COMMON WTMOLE(21),COEFFP(5),ALPHA(21,59),HCUT(59),RCOTT(59),RT(59)
       1,T(59),H(21,59),RALPHA(21,59),PSI(59),RU(59),U(59),XLE(59),TITLE(1
       22),SUM(59),ETA(59),XMU(59),A(59),AWAIT(59),RHOOUT(59),UOUT(59),TOU
       3T(59),CP(21,59),HSTG(59),RHC(59),Y(59),XMAX(3),XPRT(3),CPBAR(59),S
       4IGMA(59),HBAR(59),AFITS(21,2,7),TFITS(21,4),SPECID(21)
        DIMENSION YSJET(21),YSEDGE(21)
        IFINIS=0
        IPAGE=0
        IOUT=0
        CX=0.0
        R=3.5752932                                                       066S0502
        READ(5,1)(TITLE(I),I=1,12)                                               5
        READ(5,100)MONTH,MDAY,MYEAR,MPSI,NS,IPRESS,ITURB,IAX2D,IVAR             12
        NPSI=MPSI-1                                                       066S0528
        READ(5,1000)XPRT(1),XMAX(1),XPRT(2),XMAX(2),XPRT(3),XMAX(3),X           22
        READ(5,1000) XLE(1),SIGMA(1),YJET,XMUK1,XMUK2                           23
        READ(5,1000) (COEFFP(I),I=1,5)                                          24
        DO 50 J=1,NS
        READ(5,2000) SPECID(J),WTMOLE(J),(TFITS(J,K),K=1,4)                     33
        READ(5,1000) (AFITS(J,1,K),K=1,7)                                       40
        READ(5,1000) (AFITS(J,2,K),K=1,7)                                       45
     50 CONTINUE
        IF(IVAR.NE.0) GO TO 40
        READ(5,1000) TJET,TEDGE,UJET,UEDCE                                      55
        READ(5,1000) (YSJET(J),J=1,NS)                                          56
        READ(5,1000) (YSEDGE(J),J=1,NS)                                         63
        CUM=0.0
        P=COEFFP(1)
        DO 37 J=1,NS
     37 CUM=CUM+YSJET(J)/WTMOLE(J)
        RHOJ=P/89517.5C1/TJET/CUM
        IF(IAX2D.EQ.0) DELPSI=YJET*SQRT(RHOJ*UJET)/FLOAT(MPSI-1)                79
        IF(IAX2D.EQ.1) DELPSI=YJET*RHOJ*UJET/FLOAT(MPSI-1)
        DO 38 I=1,MPSI
        T(I)=TJET
        U(I)=UJET
```

TABLE A-III. FLOW FIELD COMPUTER PROGRAM (Continued)

```
      DO 38 J=1,NS
   38 ALPHA(J,I)=YSJET(J)
      MPSI=MPSI+2
      NPSI=MPSI-1                                                   06050114
      T(MPSI)=TEDGE
      T(NPSI)=TEDGE
      U(MPSI)=UEDGE
      U(NPSI)=UEDGE
      DO 39 J=1,NS
      ALPHA(J,MPSI)=YSEDGE(J)
   39 ALPHA(J,NPSI)=YSEDGE(J)
      GO TO 60
   40 DELPSI=YJET
      NPSI=MPSI-1

         FROZ2       - EFN    SOURCE STATEMENT  -  IFN(S)  -        03/09/70

      READ(5,1000)(T(I),I=1,MPSI)                                        114
      READ(5,1000) (U(I),I=1,MPSI)                                       121
      DO 41  I=1,MPSI
      READ(5,1000) (ALPHA(J,I),J=1,NS)                                   13C
   41 CONTINUE
   60 RETURN
    1 FORMAT(12A6)                                                  06650646
  100 FORMAT(14I5)
 1000 FORMAT(7E10.8)                                                06650648
 2000 FORMAT(A6,4X,5E1C.8)
      END                                                           06650649
         FROZ3       - EFN    SOURCE STATEMENT  -  IFN(S)  -

      SUBROUTINE FROZ1
      COMMON K,X,DPDX,POUT,HE,PE,DPDUT,P,DELPSI,CX,XMUT,XMUL,DEL,XMUK1,X
     1MUK2,PRNT,PCNT,UE,RHOE,TE,XP3,RHALF
      COMMON IOUT,MPSI,MHALF,MINIT,IFINIS,NPSI,IPAGE,IPRESS,ISTART,ITURB
     1,ITURA,IJET,NS,MDAY,MONTH,MYEAR,IAX2C,IVAR
      COMMON WTMOLE(21),COEFFP(5),ALPHA(21,59),HCUT(59),ROOTT(59),RT(59)
     1,T(59),H(21,59),RALPHA(21,59),PSI(59),RU(59),U(59),XLE(59),TITLE(1
     22),SUM(59),ETA(59),XMU(59),A(59),AWAIT(59),RHOOUT(59),UOUT(59),TOU
     3T(59),CP(21,59),HSTG(59),RHO(59),Y(59),XMAX(3),XPRT(3),CPBAR(59),S
     4IGMA(59),HBAR(59),AFITS(21,2,7),TFITS(21,4),SPECID(21)
      P=COEFFP(1)+X*(COEFFP(2)+X*(COEFFP(3)+X*(CCEFFP(4)+X*CCEFFP(5)))) 066S1396
      DPDX=COEFFP(2)+X*(2.*COEFFP(3)+X*(3.*COEFFP(4)+X*COEFFP(5)*4.)) 066S1397
      DO 1 I=1,MPSI
      ROOTT(I)=SQRT(T(I))                                                  6
      AWAIT(I)=0.C                                                  066S1440
      DO 2 J=1,NS
    2 AWAIT(I)=AWAIT(I)+ALPHA(J,I)/WTMCLE(J)
    1 RHO(I)=P/89517.501/T(I)/AWAIT(I)
      DO 20  I=1,MPSI
      DO 1C  J=1,NS
      K=1
      IF(T(I).GT.TFITS(J,2)) K=2
      CP(J,I)=(AFITS(J,K,1)+T(I)*(AFITS(J,K,2)+T(I)*(AFITS(J,K,3)+T(I)*(
     1AFITS(J,K,4)+T(I)*AFITS(J,K,5)))))*1.987*1.8/WTMCLE(J)
      H(J,I)=(AFITS(J,K,6)+T(I)*(AFITS(J,K,1)+T(I)*(AFITS(J,K,2)/2.+T(I)
     1*(AFITS(J,K,3)/3.+T(I)*(AFITS(J,K,4)/4.+T(I)*AFITS(J,K,5)/5.)))))
     2*1.987*1.8/WTMOLE(J)
   10 CONTINUE
      CPBAR(I)=0.0
      HBAR(I)=0.0
      DO 3C  J=1,NS
      CPBAR(I)=CPBAR(I)+CP(J,I)*ALPHA(J,I)
   30 HBAR(I)=HBAR(I)+H(J,I)*ALPHA(J,I)
   20 CONTINUE
      Y(1)=0.0                                                      066S1535
      DO 25 I=2,MPSI                                                C60S0240
      IF(IAX2D.EQ.0)
```

TABLE A-III. FLOW FIELD COMPUTER PROGRAM (Continued)

```
      1Y(I)=SQRT(Y(I-1)**2+DELPSI*(PSI(I)/RHO(I)/U(I)+PSI(I-1)/RHO(I-1)/U060S0241
      2(I-1)))                                                                    88
      IF(IAX20.EQ.1)
      1Y(I)=Y(I-1)+DELPSI*(1./RHO(I)/U(I)+1./RHO(I-1)/U(I-1))/2.
   25 CONTINUE
      IF(ITURB.NE.C) GO TO 4C
      XMUT=0.0
      DO 23 I=1,MPSI
   23 XMU(I)=XMUK1*T(I)*ROOTT(I)/(T(I)+111.)+XMUT                     066S1549
      XMUL=XMU(1)
      GO TO 100                                                      066S1556
   40 GO TO(26,45,6C,1001),ITURA
   45 DUM=.5*(RHO(1)*U(1)+RHO(MPSI)*U(MPSI))                         066S1558
      DO 52 J=1,MPSI                                                 066S1559
      I=MPSI-J+1                                                     066S1560
      IF(RHO(I)*U(I)-DUM) 51,51,52                                   066S1561
   52 CONTINUE                                                       066S1562
   51 DEL=Y(I)-(Y(I)-Y(I+1))*(RHC(I)*U(I)-DUM)/(RHC(I)*U(I)-RHC(I+1)*U(1066S1563
          FROZ3       -  EFN    SOURCE STATEMENT  -  IFN(S)  -

     1+1))                                                           066S1564
   55 XMUT=XMUK2*DEL*ABS(RHO(1)*U(1)-RHC(MPSI)*U(MPSI))
      GO TO 100
 1001 IF(ABS(U(1)-U(2)).LT.0.CC2*U(1)) GO TO 1004
      IF(U(MPSI) .GT. 20.)GO TC 1003
      ITURB=1
      ITURA=1
      GO TO 26
 1003 ITURB=3
      ITURA=3
      GO TC 60
 1004 ROUT=RHO(1)*U(1)
      RUNT=RHO(MPSI)*U(MPSI)
      XMUT=X*(RUNT+ROUT)/900.+1.E-04
      DO 99 I=1,MPSI
   99 XMU(I)=XMUT
      GO TO 100
   26 CONTINUE
      DUM=C.5*(RHO(1)*U(1)+RHC(MPSI)*U(MPSI))
      DO 831 II=1,MPSI
      I=II
      IM=II-1
      IF(RHO(1)*U(1).GT.DUM) I=MPSI-II+1
      IF(RHO(1)*U(1).GT.DUM) IM=I-1
      IF(RHO(I)*U(I)-DUM) 831,832,832
  831 CONTINUE
  832 RHALF=Y(I)-(Y(I)-Y(IM))*(RHC(I)*U(I)-DUM)/(RHO(I)*U(I)-RHO(IM)*U(I
     1M))
      GO TC 733
   6C CONTINUE
      DUM1=0.5*(U(1)+U(MPSI))
      DUM2=0.99*U(1)+0.01*U(MPSI)
      DO 731 I=2,MPSI
      IF((U(I-1)-DUM1)*(U(I)-DUM1).LE.C.0)I1=I
      IF((U(I-1)-DUM2)*(U(I)-DUM2).LE.C.C)I2=I
  731 CONTINUE
      RONE=Y(I1)-(Y(I1)-Y(I1-1))*(U(I1)-DUM1)/(U(I1)-U(I1-1))
      RTWO=Y(I2)-(Y(I2)-Y(I2-1))*(U(I2)-DUM2)/(U(I2)-U(I2-1))
      RHALF=ABS(RONE-RTWO)
  733 DO 833 I=1,MPSI
  833 XMU(I)=XMUK2*RHALF*RHO(1)*U(1)
      IF(RHALF*(RHALF-Y(MPSI)).GT.C.0)CALL EXIT                                  231
      XMUT=XMU(1)
  100 RETURN                                                         066S1592
      END                                                            066S1603
          FROZ4       -  EFN    SOURCE STATEMENT  -  IFN(S)  -

      SUBROUTINE EXPLIC                                              066S1944
      COMMON R,X,DPDX,PILT,HE,FF,DPOUT,F,DELPSI,CX,XMUT,XMUL,DEL,XMUK1,X
```

```
      1MUK2,PRNT,PCNT,UE,RHOE,TE,XP3,RHALF
       COMMON IOUT,MPSI,MHALF,MINIT,IFINIS,NPSI,IPAGE,IPRESS,ISTART,ITURB
      1,ITURA,IJET,NS,MDAY,MONTH,MYEAR,IAX2D,IVAR
       COMMON WTMOLE(21),COEFFP(5),ALPHA(21,59),HOUT(59),RCOTT(59),RT(59)
      1,T(59),H(21,59),RALPHA(21,59),PSI(59),RU(59),U(59),XLE(59),TITLE(1
      22),SUM(59),ETA(59),XMU(59),A(59),AWAIT(59),RHOOUT(59),UOUT(59),TOU
      3T(59),CP(21,59),HSTG(59),RHO(59),Y(59),XMAX(3),XPRT(3),CPBAR(59),S
      4IGMA(59),HBAR(59),AFITS(21,2,7),TFITS(21,4),SPECID(21)
       IF(IAX2D.EQ.0) DX=DELPSI*DELPSI*SIGMA(1)/XMU(1)/XLE(1)/12.0
       IF(IAX2D.EQ.1)DX=DELPSI**2*SIGMA(1)/XMU(1)/XLE(1)/RHO(1)/U(1)/6.0
       DO 10 I=2,NPSI                                                   06CS0369
       CIVIS=A(I+1)+A(I-1)+A(I)+A(I)                                    060S0370
       DELX=DELPSI**2*SIGMA(I)/XLE(I)/CIVIS/1.5
       IF(IAX2D.EQ.0) DELX=DELX*PSI(I)
   10 DX=AMIN1(DX,DELX)
       DIFY = Y(2) - Y(1)
       IF(DX-DIFY)162,162,163
  163 DX=DIFY/2.
  162 CONTINUE
       DO 100 I=2,NPSI                                                  066S2000
       EX1=DELPSI**2/DX
       IF(IAX2D.EQ.0) EX1=EX1*PSI(I)
       EX11=.5*(A(I)+A(I+1))                                            066S2002
       EX12=.5*(A(I)+A(I-1))                                            066S2003
       RU(I)=(EX11*(U(I+1)-U(I))+EX12*(U(I-1)-U(I)))/EX1+U(I)           066S2004
       EX4=0.0                                                          066S2025
       DO 20  J=1,NS
   20 EX4=EX4+CP(J,I)*(ALPHA(J,I+1)-ALPHA(J,I-1))                       066S2028
       EX2=EX1*CPBAR(I)                                                 066S2029
       EX5=XLE(I)*A(I)/SIGMA(I)                                         066S2030
       EX6=.5*(EX5+XLE(I+1)*A(I+1)/SIGMA(I+1))                          066S2031
       EX7=.5*(EX5+XLE(I-1)*A(I-1)/SIGMA(I-1))                          066S2032
       EX8=CPBAR(I)*A(I)/SIGMA(I)                                       066S2033
       EX9=.5*(EX8+CPBAR(I+1)*A(I+1)/SIGMA(I+1))                        066S2034
       EX10=.5*(EX8+CPBAR(I-1)*A(I-1)/SIGMA(I-1))                       066S2035
       EX13=EX1-EX6-EX7                                                 066S2036
       EX14=EX4*EX5/4.                                                  066S2037
       RT(I)=(U(I+1)-U(I-1))**2*A(I)/EX2/100151.23+((EX9+EX14)*T(I+1)+(EX
      110-EX14)*T(I-1)+(EX2-EX9-EX10)*T(I))/EX2
       DO 40 J=1,NS
   40 RALPHA(J,I)=(EX6*ALPHA(J,I+1)+EX13*ALPHA(J,I)+EX7*ALPHA(J,I-1))/EX
      11
       RT(I)=RT(I)+DX*DPDX/RHO(I)/CPBAR(I)/25037.807
       RU(I)=RU(I)-DX*DPDX/RHO(I)/U(I)
  100 CONTINUE                                                          066S2060
       IF(IAX2D.EQ.0) EX16=4.0*XMU(1)*DX/DELPSI/DELPSI
       IF(IAX2D.EQ.1) EX16=2.0*XMU(1)*DX*RHO(1)*U(1)/DELPSI**2
       RU(1)=-DX*DPDX/RHO(1)/U(1)+EX16*(U(2)-U(1))+U(1)
       DO 200 J=1,NS
  200 RALPHA(J,1)=EX16*XLE(1)*(ALPHA(J,2)-ALPHA(J,1))/SIGMA(1)+ALPHA(J,
      11)
       RT(1)=DX*DPDX/RHO(1)/CPBAR(1)/25037.807+EX16*(T(2)-T(1))/SIGMA(1)+
      1T(1)
            FROZ4       -  EFN   SOURCE STATEMENT  -  IFN(S)  -

       DFL=DX                                                           066S2137
       IF(IFINIS)50,1,50                                                066S2138
    1 IFINIS=1                                                          066S2139
       MINIT=MPSI
       MHALF=MPSI+MPSI-1                                                066S2146
   50 CONTINUE
       X=X+DX                                                           066S2156
       DO 30 I=1,59
       DO 5 J=1,NS
    5 ALPHA(J,I)=RALPHA(J,I)                                            066S2162
       T(I)=RT(I)                                                       066S2164
   30 U(I)=RU(I)
 1000 IF(MPSI-MHALF)999,1500,1500
  999 IF(ABS(U(NPSI)-U(MPSI))-.001*U(MPSI)) 1001,1004,1004
 1001 IF(ABS(T(NPSI)-T(MPSI))-.001*T(MPSI))1002,1004,1004
```

TABLE A-III. FLOW FIELD COMPUTER PROGRAM (Continued)

```
1002 DO 1003  J=1,NS
     IF(ALPHA(J,MPSI)-1.E-30) 1003,1003,1222                          066S2336
1222 IF(ABS(ALPHA(J,NPSI)-ALPHA(J,MPSI))-.001*ALPHA(J,MPSI))1003,1003,1
    1004
1003 CONTINUE                                                         066S2339
     GO TO 2000                                                       066S2340
1004 MPSI=MPSI+1                                                      066S2341
     NPSI=MPSI-1                                                      066S2342
     GO TO 2000
1500 IFINIS=0                                                         066S2377
     CALL FROZ1                                                                 159
     CALL COMPUT                                                                161
     IF(IFINIS.GT.1) RETURN
     DELPSI=DELPSI+DELPSI                                             066S2388
     DO 1600 I=1,MINIT                                                066S2389
     U(I)=U(2*I-1)                                                    066S2390
     DO 1650 J=1,NS
1650 ALPHA(J,I)=ALPHA(J,2*I-1)                                        066S2393
1600 T(I)=T(2*I-1)                                                    066S2394
     MPSI=MINIT                                                       066S2395
     NPSI=MPSI-1                                                      066S2396
     DO 1700 I=MINIT,59                                               066S2400
     T(I)=T(MPSI)                                                     066S2403
     RT(I)=T(MPSI)
     DO 1750 J=1,NS
     ALPHA(J,I)=ALPHA(J,MPSI)                                         066S2406
1750 RALPHA(J,I)=ALPHA(J,MPSI)                                        066S2407
     RU(I)=U(MPSI)                                                    066S2408
1700 U(I)=U(MPSI)                                                     066S2409
     DO 1800 I=2,59                                                   066S2410
1800 PSI(I)=PSI(I-1)+DELPSI                                           066S2411
2000 RETURN
     END                                                              066S2428

        FROZ5        -  EFN    SOURCE STATEMENT   -  IFN(S)  -

     SUBROUTINE INITAL                                                066S0651
     COMMON R,X,DPCX,POUT,HE,PE,DPOUT,F,DELPSI,CX,XMUT,XMUL,DEL,XMUK1,X
    1MUK2,PRNT,PCNT,UE,RHOE,TE,XP3,RHALF
     COMMON IOUT,MPSI,MHALF,MINIT,IFINIS,NPSI,IPAGE,IPRESS,ISTART,ITURB
    1,ITURA,IJET,NS,MDAY,MONTH,MYEAR,IAX2D,IVAR
     COMMON ATMOLE(21),COEFFP(5),ALPHA(21,59),HCUT(59),ROCTT(59),RT(59)
    1,T(59),H(21,59),RALPHA(21,59),PSI(59),RU(59),U(59),XLE(59),TITLE(1
    22),SUM(59),ETA(59),XMU(59),A(59),AWAIT(59),RHOOUT(59),UOUT(59),TOU
    3T(59),CP(21,59),HSTG(59),RHO(59),Y(59),XMAX(3),XFRT(3),CPBAR(59),S
    4IGMA(59),HBAR(59),AFITS(21,2,7),TFITS(21,4),SPECID(21)
     XP3=0.0
     ITURA=IABS(ITURB)
     DEL=CX                                                           066S0680
     IFLAG1=0
     DO 220 I=1,MPSI
     DUMA=0.0
     DO 10 J=1,NS
  10 DUMA=DUMA+ALPHA(J,I)
     IF(DUMA.EQ.0.0)GO TO 220
  14 IF(ABS(DUMA-1.)-.01)13,13,100
 100 WRITE(6,111)DUMA,I                                                          17
     IFLAG1=1
 111 FORMAT(13H0SIGMA ALPHA =1PE15.7,12HPOINT NUMBERI5,6HIN PSI)       066S0696
  13 DO 15 J=1,NS
  15 ALPHA(J,I)=ALPHA(J,I)/DUMA                                       066S0698
 220 CONTINUE                                                         066S0699
     IF(IFLAG1.EQ.1) CALL EXIT                                                   29
     DO 228 I=2,59                                                    066S0700
     XLE(I)=XLE(1)                                                    066S0701
     SIGMA(I)=SIGMA(1)                                                066S0702
 228 PSI(I)=PSI(I-1)+DELPSI                                           066S0703
     DUMMY=3.05E-8                                                    066S0704
  29 P=COEFFP(1)+X*(COEFFP(2)+X*(COEFFP(3)+X*(COEFFP(4)+X*COEFFP(5))))
```

TABLE A-III. FLOW FIELD COMPUTER PROGRAM (Continued)

```
      DO 9C I=MPSI,59                                               066S0754
      RT(I)=T(MPSI)                                                 066S0755
      T(I)=T(MPSI)                                                  066S0756
      DO 80 J=1,NS
      RALPHA(J,I)=ALPHA(J,MPSI)                                     066S0758
   80 ALPHA(J,I)=ALPHA(J,MPSI)                                      066S0759
      RU(I)=U(MPSI)                                                 066S0762
   90 U(I)=U(MPSI)                                                  066S0766
      WRITE(6,341)(TITLE(I),I=1,12)                                         63
      IF(IAX2D.EQ.C) WRITE(6,616)                                           7C
      IF(IAX2D.EQ.1) WRITE(6,617)                                           72
      WRITE(6,888) MCNTH,MDAY,MYEAR                                         73
      WRITE(6,999)                                                          74
      WRITE(6,609)                                                          75
      WRITE(6,611)                                                          76
      WRITE(6,612)                                                          77
      WRITE(6,615)                                                          78
      WRITE(6,618)                                                          79
      IF(IPRESS-2) 6C1,6C2,604
  601 WRITE(6,701)CCEFFP(1)                                                 81
      GO TO 6C4                                                     066S0858
  6C2 WRITE(6,702)(CCEFFP(I),I=1,5)                                         83
          FROZ5      - EFN    SOURCE STATEMENT  -  IFN(S)  -

  6C4 CONTINUE
      WRITE(6,999)                                                          90
      WRITE(6,808)SIGMA(1),XLE(1)                                           91
      WRITE(6,999)                                                          92
      WRITE(6,809) ITURA                                                    93
      WRITE(6,810)XMUK1,XMUK2                                               94
      XMUK1=XMUK1*DUMMY                                             066SC866
      WRITE(6,999)                                                          95
      DO 171 I=1,3
  171 WRITE(6,812) XPRT(I),XMAX(I)                                          99
      WRITE(6,999)                                                         103
      WRITE(6,613) U(MPSI),T(MPSI)                                         104
      RETURN
  341 FORMAT(1H1,24X,33HGENERALIZED FROZEN MIXING PROGRAM/1H0,5X,12A6)
  888 FORMAT(1H0,34X,4HDATEI3,1H/,I2,1H/,I2)
  6C9 FORMAT(18H VELOCITY-(FT/SEC),20X,17HENTHALPY-(BTU/LB))
  611 FORMAT(29H TEMPERATURE-(DEGREES KELVIN),9X,22HPSI-((SLUGS/SEC)**1/
     12))
  612 FORMAT(22H DENSITY-(SLUGS/FT**3),16X,19HPRESSURE-(LB/FT**2))
  613 FORMAT(19H EDGE VELOCITY(UE)=E11.4,15X,21HEDGE TEMPERATURE(TE)=E11
     1.4)
  615 FORMAT(29H VISCOSITY(MU)-(LB*SEC/FT**2),9X,12HRADII-(FEET))
  616 FORMAT(33X,17HAXISYMMETRIC FLOW)
  617 FORMAT(32X,20HTWO DIMENSIONAL FLOW)
  618 FORMAT(25H SPECIES-(MASS FRACTIONS))
  808 FORMAT(16H PRANDTL NUMBER=F5.2,24X,13HLEWIS NUMBER=F5.2)
  809 FORMAT(18H VISCOSITY OPTION=I2)
  810 FORMAT(31H LAMINAR VISCOSITY COEFFICIENT=F5.2,9X,32HTURBULENT VISC
     1OSITY COEFFICIENT=F7.4)
  812 FORMAT(12H PRINT EVERYF7.3,5H FEET,21X,8HUNTIL X=F8.3,5H FEET)
  999 FORMAT(1H0)
  701 FORMAT(1H0,20X,23HCONSTANT PRESSURE     P=E15.7)
  702 FORMAT(1H0,3CX,63HPOLYNOMIAL PRESSURE FIT    P=A+B*(X)+C*(X**2)+D*066S0960
     1(X**3)+E*(X**4)/15X,2HA=1PE15.7,3H B=1PE15.7,3H C=1PE15.7,3H D=1PE066SC961
     215.7,3H E=1PE15.7)                                            066S0962
      END                                                           066S1008
          FROZ6      - EFN    SOURCE STATEMENT  -  IFN(S)  -

      SUBROUTINE COMPUT
      DIMENSION RJACK(60,25),PJACK(60,25),TRATEM(60,25),XJACK(60)
      COMMCN R,X,DPCX,POUT,HE,PE,DPOUT,P,DELPSI,CX,XMUT,XMUL,DEL,XMUK1,X
     1MUK2,PRNT,PCNT,UE,RHOE,TE,XP3,RHALF
      COMMON IOUT,MPSI,MHALF,MINIT,IFINIS,NPSI,IPAGE,IPRESS,ISTART,ITURB
     1,ITURA,IJET,NS,MCAY,MONTH,MYEAR,IAX2D,IVAR
```

TABLE A-III. FLOW FIELD COMPUTER PROGRAM (Continued)

```
      COMMON WTMOLE(21),COEFFP(5),ALPHA(21,59),HOUT(59),ROOTT(59),RT(59)
     1,T(59),H(21,59),RALPHA(21,59),PSI(59),RU(59),U(59),XCE(59),TITLE(1
     22),SUM(59),ETA(59),XMU(59),A(59),AWAIT(59),RHOOUT(59),UOUT(59),TOU
     3T(59),CP(21,59),HSTG(59),RHC(59),Y(59),XMAX(3),XPRT(3),CPBAR(59),S
     4IGMA(59),HBAR(59),AFITS(21,2,7),TFITS(21,4),SPECID(21)
      IOUT=IOUT+1                                                       06650024
      IF(XP3.EQ.0.C) XP3=XPRT(1)
      IF(IAX2D.EQ.C) GO TO 42
      DO 41 I=1,MPSI
   41 A(I)=XMU(I)*RHC(I)*U(I)
      GO TO 43
   42 A(1)=0.0
      A(2)=DELPSI*XMU(2)
      DO 44 I=3,MPSI
   44 A(I)=XMU(I)*RHC(I)*U(I)*Y(I)*Y(I)/PSI(I)
   43 CONTINUE
      RBARDL=X
      IF(IFINIS.EC.C) GO TO 60C
      DO 500 I=1,3
      IF(RBARDL.LT.XMAX(I))GO TO 501
  500 CONTINUE
      GO TO 888
  5C1 PRNT=XPRT(I)
      IF(RBARDL.LT.XP3) RETURN
      DO 6699 I=1,3
      IF(RBARDL.LT.XMAX(I)) GC TC 6688
 6699 CONTINUE
  888 IFINIS=2
      GO TO 555
 6688 XP3=XP3+XPRT(I)
  600 CONTINUE
  555 CONTINUE
  572 FORMAT(E10.8,I5)
      IF(X.EC.0.) READ(5,572) ROC,NORLN
      IF(X.EQ.0.) IXP=C
      IF(X.EC.0.) GC TO 8C2
      CHGX=X-PREVX
      CMPR=XPRT(1)-C.1
      IF(CHGX.LT.CMPR) RETURN
  8C2 PREVX=X
      IXP=IXP+1
      IF(IXP.EQ.61) GO TC 999
      TTEST=1.05*T(MPSI)
      XJACK(IXP)=X
      DO 525 KUNK=1,25
      RJACK(IXP,KUNK)=Y(KUNK)
      SJACK=C.0
      DO 530 KONK=1,NS
  530 SJACK=SJACK+ALPHA(KONK,KUNK)/WTMCLE(KCNK)
         FROZ6      -  EFN      SOURCE STATEMENT  -  IFN(S)  -

      PJACK(IXP,KUNK)=ALPHA(3,KUNK)/WTMCLE(3)/SJACK
      TRATEM(IXP,KUNK)=T(KUNK)
      IF(TRATEM(IXP,KUNK).LE.TTEST) GC TC 540
  525 CONTINUE
  540 IF(T(KUNK).GT.T(MPSI)) GO TC 544
  545 PJACK(IXP,KUNK)=C.C0033
      DYP=Y(KUNK-1) + Y(2)
      GO TO 548
  544 WTR1=ALOG(T(KUNK-1)/T(MPSI) - 1.)
      WTR2=ALOG(T(KUNK)/T(MPSI) -1.)
      WTRP=ALOG(0.05)
      YTR1=Y(KUNK-1)
      YTR2=Y(KUNK)
      YTRP=(YTR1*YTR1*(WTRP-WTR2)+YTR2*YTR2*(WTR1-WTRP))/(WTR1-WTR2)
      DYP=SQRT(YTRP)
      ZTR1=ALOG(PJACK(IXP,KUNK-1)-C.0CC33)
      ZTR2=ALOG(PJACK(IXP,KUNK)-C.C0033)
      BTRA=(ZTR1-ZTR2)/(YTR2*YTR2-YTR1*YTR1)
      CTRA=ZTR1+BTRA*YTR1*YTR1
```

```
      PJACK(IXP,KUNK)=0.00033+EXP(CTRA-BTRA*DYP*DYP)                                131
  548 RJACK(IXP,KUNK)=DYP
      TRATEM(IXP,KUNK)=TTEST
      IF(KUNK.EQ.25) GO TO 565
      KUNKP1=KUNK+1
      DO 564 IJK=KUNKP1,25
      PJACK(IXP,IJK)=PJACK(IXP,KUNK)
      RJACK(IXP,IJK)=RJACK(IXP,KUNK)
  564 TRATEM(IXP, IJK)=TTEST
  565 IF(IXP.NE.60) GO TO 567
      ATR=0.
      CTR=0.
      DO 566 IJK=20,60
      TY=RJACK(IJK,25)-ROO
      ATR=ATR+TY
  566 CTR=CTR+XJACK(IJK)
      DTR=ATR/CTR
      DO 568 IJK=1,6C
  568 RJACK(IJK,25)=ROC+DTR*XJACK(IJK)
      DO 573 NP=1,6C
      DO 573 IP=1,24
      IF(TRATEM(NP,IP).EQ.TTEST) RJACK(NP,IP)=RJACK(NP,25)
  573 CONTINUE
      DO 574 NP=2,6C
      IF(RJACK(NP,25).LE.RJACK(NP-1,25)) RJACK(NP,25)=RJACK(NP-1,25)+0.1
  574 CONTINUE
      WRITE(6,9000)                                                                 195
 9000 FORMAT(1H1)
 9001 FORMAT(1H ,4E12.5)
      DO 576 NP=1,6C
  576 WRITE(6,9001) XJACK(NP),RJACK(NP,25),TRATEM(NP,25),PJACK(NP,25)               199
      II=25
      DO 577 NP=1,6C
      XJACK(NP)=XJACK(NP)*30.48
      DO 578 KK=1,25
  578 RJACK(NP,KK)=RJACK(NP,KK)*30.48
  577 CONTINUE
          FROZ6      -  EFN   SOURCE STATEMENT  -  IFN(S)  -

      DIMENSION CAT(25),RAT(25),PAT(25)
      DO 750 NXP=1,6C
      DO 751 NRP=1,25
      IF(TRATEM(NXP,NRP).EQ.TTEST) GO TO 752
  751 CONTINUE
  752 RAMAX=RJACK(NXP,NRP)
      NATPL=NRP
      DO 753 NN=1,NRP
      IF(RJACK(NXP,NN).GT.RAMAX) GO TO 754
  753 CONTINUE
      GO TO 755
  754 NRP=NN
      RX=(RJACK(NXP,NRP-1)+RJACK(NXP,NRP+1))/2.
      PT1=(TRATEM(NXP,NRP-1)-T(MPSI))/(TRATEM(NXP,NRP+1)-T(MPSI))
      IF(PT1.LT.1.0) PT1=1.0
      PT2=-ALOG(PT1)                                                                254
      PT3=RX*RX-RJACK(NXP,NRP-1)**2
      PT4=RJACK(NXP,NRP+1)**2-RJACK(NXP,NRP-1)**2
      PT5=(PT3/PT4)*PT2
      PT6=TRATEM(NXP,NRP-1)-T(MPSI)
      TRATEM(NXP,NRP)=T(MPSI)+PT6*EXP(PT5)                                          263
      PT1=((PJACK(NXP,NRP-1)-0.00033))/(PJACK(NXP,NRP+1)-0.00033)
      IF(PT1.LT.1.0) PT1=1.0
      PT2=-ALOG(PT1)                                                                270
      PT5=(PT3/PT4)*PT2
      PT6=PJACK(NXP,NRP-1)-0.00033
      PJACK(NXP,NRP)=0.00033+PT6*EXP(PT5)                                           272
      RJACK(NXP,NRP)=RX
  755 CONTINUE
      DELTR=RAMAX/24.
      DO 756 NRP=2,25
```

```
      CNT=NRP-1
      RAT(NRP)=CNT*DELTR
      PI=0.00033
      TI=T(MPSI)
      DO 757 IJK=2,NATPL
      IF(RAT(NRP).LT.RJACK(NXP,IJK)) GO TO 758
 757  CONTINUE
 758  R1=RJACK(NXP,IJK-1)
      R2=RJACK(NXP,IJK)
      RX=RAT(NRP)
      T1=TRATEM(NXP,IJK-1)
      T2=TRATEM(NXP,IJK)
      P1=PJACK(NXP,IJK-1)
      P2=PJACK(NXP,IJK)
      PT1=(RX*RX-R1*R1)/(R2*R2-R1*R1)
      PT2=(T1-TI)/(T2-TI)
      IF(PT2.LT.1.0) PT2=1.0
      PT2=-ALOG(PT2)*PT1                                              295
      CAT(NRP)=TI+(T1-TI)*EXP(PT2)                                    300
      PT2=(P1-PI)/(P2-PI)
      IF(PT2.LT.1.0) PT2=1.0
      PT2=-ALOG(PT2)*PT1                                              304
      PAT(NRP)=PI+(P1-PI)*EXP(PT2)                                    305
 756  CONTINUE
      DO 759 JK=2,25
        FRUZ6       -  EFN    SOURCE STATEMENT  -  IFN(S)  -

      RJACK(NXP,JK)=RAT(JK)
      PJACK(NXP,JK)=PAT(JK)
 759  TRATEM(NXP,JK)=CAT(JK)
      WRITE(10)(TITLE(I),I=1,12)                                      318
      WRITE(10) NURUN                                                 323
      DO 579 NP=1,60
      WRITE(10)   XJACK(NP),II                                        325
      WRITE(10)(TRATEM(NP,JJ),RJACK(NP,JJ),PJACK(NP,JJ),JJ=1,25)      327
 579  CONTINUE
      WRITE(6,786) XJACK(NXP)                                         335
      DO 780 JK=1,25
 780  WRITE(6,787)RJACK(NXP,JK),TRATEM(NXP,JK),PJACK(NXP,JK)          339
 750  CONTINUE
 786  FORMAT(1H ,E11.4)
 787  FORMAT(1H ,3E15.4)
 567  DO 25 II=1,MPSI
      I=MPSI+1-II                                                066S0051
      TOUT(I)=T(I)/T(MPSI)
      UOUT(I)=U(I)/U(MPSI)                                       066S0055
      RHOOUT(I)=RHO(I)/RHO(MPSI)                                 066S0056
      HSTG(I)=HBAR(I)+U(I)*U(I)/50075.614                        066S0057
      HOUT(I)=HSTG(I)/HSTG(MPSI)                                 066S0058
      SUM(I)=0.0                                                 066S0059
      DO 11 J=1,NS
  11  SUM(I)=SUM(I)+ALPHA(J,I)                                   066S0061
  25  CONTINUE
      IPAGE=IPAGE+1                                              066S0182
      WRITE(6,201)(TITLE(I),I=1,12),IPAGE                             379
      WRITE(6,721) NCRUN                                              386
 721  FORMAT(1H0,10HRUN NUMBER,I4)
      WRITE(6,102) X,DX,IOUT                                          387
      WRITE(6,608)XMLL,XMUT,RHALF                                     388
      WRITE(6,609) F,DPDX                                             389
      WRITE(6,107)                                                    390
      DO 10 I=1,MPSI
  10  WRITE(6,207)I,UOUT(I),TOUT(I),RHOOUT(I),HOUT(I),SUM(I),Y(I),PSI(I)
     1,I                                                              394
      K=MINO(7,NS)
      WRITE(6,201)(TITLE(I),I=1,12),IPAGE                             404
      WRITE(6,108) (SPECID(I),I=1,K)                                  411
      DO 20 I=1,MPSI
  20  WRITE(6,208) I,(ALPHA(J,I),J=1,K)                               421
      IF(NS.LE.7) RETURN
```

TABLE A-III. FLOW FIELD COMPUTER PROGRAM *(Concluded)*

```
      K=MINO(14,NS)
      WRITE(6,201)(TITLE(I),I=1,12),IFACE                          430
      WRITE(6,108) (SPECID(I),I=8,K)                               437
      DO 34 I=1,MPSI
   34 WRITE(6,208) I,(ALPHA(J,I),J=8,K)                            447
      IF(NS.LE.14) RETURN
      K=MINO(21,NS)
      WRITE(6,201)(TITLE(I),I=1,12),IPAGE                          456
      WRITE(6,108) (SPECID(I),I=15,K)                              463
      DO 35 I=1,MPSI
   35 WRITE(6,208) I,(ALPHA(J,I),J=15,K)                           473
      RETURN
  999 IF IN IS=2
          FRUZ6      -  EFN   SOURCE STATEMENT  -  IFN(S)  -

      RETURN
  208 FORMAT(I3,7E11.3)
  108 FORMAT(3HOPT,7(3X,A6,2X))
  201 FORMAT(1H1,3X,12A6,2X,4HPAGEI3)
  207 FORMAT(I3,7E15.6,I4)
  107 FORMAT(3HOPT,6X,4HU/UE,11X,4HT/TE,9X,8HRHO/RHOE,9X,4HH/HE,10X,5HSI
     IGMA,12X,1HY,13X,3HPSI,7X,2HPT)
  608 FORMAT(6HOMU L=E13.5,7X,5HMU T=E13.5,13X,6HRHALF=E13.5)
  609 FORMAT(3HOP=E11.3,10X,5HDPDX=E11.3)
  102 FORMAT(3HOX=E13.5,10X,8HDELTA X=E13.5,10X,6HSTEPS=I4)
      END                                                     J6650478
```

TABLE A-IV. TYPICAL OUTPUT DATA

```
                      GENERALIZED FROZEN MIXING PROGRAM
      TYPICAL TURBOJET AIRCRAFT - SEA LEVEL CONDITIONS - 900 DEG EGT STATIC
                               AXISYMMETRIC FLOW

                               DATE  3/ 6/70

VELOCITY-(FT/SEC)                           ENTHALPY-(BTU/LB)
TEMPERATURE-(DEGREES KELVIN)                PSI-((SLUGS/SEC)**1/2)
DENSITY-(SLUGS/FT**3)                       PRESSURE-(LB/FT**2)
VISCOSITY(MU)-(LB*SEC/FT**2)                RADII-(FEET)
SPECIES-(MASS FRACTIONS)

                  CONSTANT PRESSURE    P=  0.2117000E 04

PRANDTL NUMBER= 0.71                        LEWIS NUMBER= 1.40

VISCOSITY OPTION= 4
LAMINAR VISCOSITY COEFFICIENT= 0.           TURBULENT VISCOSITY COEFFICIENT= 0.0285

PRINT EVERY  0.250 FEET                     UNTIL X=  10.000 FEET
PRINT EVERY  1.000 FEET                     UNTIL X=  20.000 FEET
PRINT EVERY  2.000 FEET                     UNTIL X=  50.000 FEET

EDGE VELOCITY(UE)= 0.100CE 01               EDGE TEMPERATURE(TE)= 0.3000E 03

    TYPICAL TURBOJET AIRCRAFT - SEA LEVEL CONDITIONS - 900 DEG EGT STATIC     PAGE  1

RUN NUMBER   1

X=  0.                DELTA X=  0.                   STEPS=   1

MU L= -0.000000E-19      MU T=  0.1000CE-03          RHALF= -0.00000E-19

P=  0.212E 04            DPDX= -0.
```

PT	U/UE	T/TE	RHO/RHOE	H/HE	SIGMA	Y	PSI	PT
1	0.180000E 04	0.300000E 01	0.333567E 00	-0.280078E 02	0.100000E 01	0.	-0.000000E-19	1
2	0.180000E 04	0.300000E 01	0.333567E 00	-0.280078E 02	0.100000E 01	0.111111E 00	0.129844E 00	2
3	0.180000E 04	0.300000E 01	0.333567E 00	-0.280078E 02	0.100000E 01	0.222222E 00	0.259688E 00	3
4	0.180000E 04	0.300000E 01	0.333567E 00	-0.280078E 02	0.100000E 01	0.333333E 00	0.389532E 00	4
5	0.180000E 04	0.300000E 01	0.333567E 00	-0.280078E 02	0.100000E 01	0.444444E 00	0.519376E 00	5
6	0.180000E 04	0.300000E 01	0.333567E 00	-0.280078E 02	0.100000E 01	0.555556E 00	0.649220E 00	6
7	0.180000E 04	0.300000E 01	0.333567E 00	-0.280078E 02	0.100000E 01	0.666667E 00	0.779064E 00	7
8	0.180000E 04	0.300000E 01	0.333567E 00	-0.280078E 02	0.100000E 01	0.777778E 00	0.908908E 00	8
9	0.180000E 04	0.300000E 01	0.333567E 00	-0.280078E 02	0.100000E 01	0.888889E 00	0.103875E 01	9
10	0.180000E 04	0.300000E 01	0.333567E 00	-0.280078E 02	0.100000E 01	0.100000E 01	0.116860E 01	10
11	0.100000E 01	0.100000E 01	0.100000E 01	0.100000E 01	0.100000E 01	0.867354E 01	0.129844E 01	11
12	0.100000E 01	0.100000E 01	0.100000E 01	0.100000E 01	0.100000E 01	0.151955E 02	0.142828E 01	12

TABLE A-IV. TYPICAL OUTPUT DATA (Concluded)

TYPICAL TURBOJET AIRCRAFT – SEA LEVEL CONDITIONS – 900 DEG EGT STATIC PAGE 1

PT	O2	N2	CO2	H2O
1	0.175E 00	0.753E 00	0.520E-01	0.198E-01
2	0.175E 00	0.753E 00	0.520E-01	0.198E-01
3	0.175E 00	0.753E 00	0.520E-01	0.198E-01
4	0.175E 00	0.753E 00	0.520E-01	0.198E-01
5	0.175E 00	0.753E 00	0.520E-01	0.198E-01
6	0.175E 00	0.753E 00	0.520E-01	0.198E-01
7	0.175E 00	0.753E 00	0.520E-01	0.198E-01
8	0.175E 00	0.753E 00	0.520E-01	0.198E-01
9	0.175E 00	0.753E 00	0.520E-01	0.198E-01
10	0.175E 00	0.753E 00	0.520E-01	0.198E-01
11	0.232E 00	0.768E 00	0.500E-03	0.
12	0.232E 00	0.768E 00	0.500E-03	0.

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13. ABSTRACT

This report describes an analytical model for predicting the emission of radiation from a jet plume in the mid-infrared spectral region. It is assumed that the dominant radiation arises for the CO_2 molecule. Results are therefore reported for the 4.3-micrometer band of gaseous carbon dioxide which is assumed to cover the spectral region 2050 to 2400/cm^{-1} (4.17 - 4.88 micrometers). The temperature range that is considered varies from 200° to 2100°K. The objective of the reported program was to develop a computerized program for predicting radiant energy emissions which could be readily integrated into a flow field calculation. A description is given of both the radiation model and the flow field model. The described program provides both the spectral and spatial intensity distributions of the emitted radiation.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Jet plume radiation Mid-infrared spectral region CO_2 molecule Radiant energy emission Flow field model						